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A SUMMARY OF THE EVALUATION OF PPG HERCULITE XP GLASS IN PUNCHED WINDOW AND STOREFRONT ASSEMBLIES

Kirk A. Marchand, Carrie E. Davis, Ryan M. Alberson, Baktosh H. Edrisi, and Edward J. Conrath
Protection Engineering Consultants, LLC
P.O. Box 78607
San Antonio, TX 78278

Brian Kornish
PPG Industries, Inc.
6506 Greycliff Heights Drive
St Louis, MO 63129

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ALBERT N. RHODES, PhD
Chief, Airbase Technologies Division

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6. AUTHOR(S)

*Marchand, Kirk A.; *Davis, Carrie, E.; *Alberson, Ryan, M.;
*Edrisi, Baktosh, H.; *Conrath, Edward J.; **Kornish, Brian

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

*Protection Engineering Consultants, LLC; PO Box 781607; San Antonio, TX 78278
**PPG Industries, Inc.; 6506 Greycliff Heights Drive, St Louis, MO 63129

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14. ABSTRACT

Protection Engineering Consultants (PEC) was engaged by AFRL to evaluate the performance of Herculite® XP glass used in standard commercial window configurations and frames for force protection applications. Herculite® XP is a high-strength glass technology with a residual stress about twice that of commercially produced fully tempered glass. The research program included quasi-static tests of Herculite® XP glass at PEC and shock tube tests of punched windows (Herculite® XP insulating glass units (IGUs) with commercial window frames) at ABS Consulting, on Herculite® XP IGUs in punched window and storefront configurations using commercially available window frames. The main goals of this research program were to evaluate the performance of Herculite® XP window systems, confirm parameters for use in fast running design tools, and develop a robust and conservative design method for specifying Herculite® XP. The SDOF analysis tool conservatively predicted the performance of Herculite® XP IGUs in standard layups subjected to dynamic loads. In general, Herculite® XP can provide the same level of protection as annealed (AN), heat strengthened (HS), or FT glass using a thinner and lighter section. A design method was also outlined to incorporate Herculite® XP glass into existing industry standards, such as ASTM E1300.

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high strength glass, blast testing, window and mullion design, human injury

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PREFACE

PPG provided material to a program to evaluate high-strength glass, specifically Herculite® XP, for use in commercial window systems to protect in blast overload situations. Herculite® XP is a PPG Industries glass product with roughly twice the residual stress as typical fully tempered (FT) glass. Evaluation of the window system was performed with full-scale static and dynamic tests to investigate glass and mullion performance. As a result of several successful tests series, data was gathered to develop a design procedure to allow engineers to specify Herculite® XP per industry standards. This report focuses specifically on the performance of Herculite® XP glass; however conclusions generally apply to all types of high-strength glass.

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1. EXECUTIVE SUMMARY

Protection Engineering Consultants (PEC) was engaged to evaluate the performance of Herculite® XP glass used in standard commercial window configurations and frames for antiterrorism/force protection (ATFP) applications. Herculite® XP is a high-strength glass technology with a residual stress about twice that of commercially produced, fully tempered (FT) glass. The research program included quasi-static tests of Herculite® XP glass at PEC, shock tube tests of punched windows (Herculite® XP insulating glass units (IGUs) with commercial window frames) at ABS Consulting (ABS), and a full-scale blast test on Herculite® XP IGUs in punched-window and storefront configurations using commercially available window frames. The main goals of this research program were to evaluate the performance of Herculite® XP window systems, confirm parameters for use in fast running design tools, and develop a robust and conservative design method for specifying Herculite® XP.

First, Herculite® XP glass was evaluated statically and dynamically to confirm and update design parameters from a previous research program with PPG Industries on the development of Herculite® XP. The design parameters were used in a robust resistance function for dynamic, single-degree-of-freedom (SDOF) analysis of Herculite® XP. The SDOF analysis tool conservatively predicted the performance of Herculite® XP IGUs in standard layups subjected to shock tube and blast loads. In general, Herculite® XP can provide the same level of protection as annealed (AN), heat strengthened (HS), or FT glass using a thinner and lighter section.

Next, Herculite® XP glass was tested dynamically in punched-window and storefront configurations using standard commercial mullion framing systems. Tests illustrated that commercial mullion systems can successfully support Herculite® XP glass when subjected to blast loads. Blast tests also illustrated that for blast loads with high pressures the glass and mullion response was essentially uncoupled and can be conservatively designed using SDOF analysis. However, a coupled analysis may be more appropriate for more complex curtain wall systems with varying support conditions. Thus, data collected will help validate future multi-degree-of-freedom (MDOF) design tools of glass and mullion systems.

Next, a design method was developed to enable engineers to specify Herculite® XP for windows. Herculite® XP glass can be incorporated into existing industry standards, such as ASTM E1300 (2012), using an approach outlined by the ASTM task group with minor modifications. Data collected during the test programs was used to adjust the approach specifically for Herculite® XP applications. A full design example is provided and includes all design assumptions.

2. INTRODUCTION

Architectural systems that provide protection and that satisfy environmental, aesthetic, and functional requirements in addition to saving money are a great benefit. In 2009, PEC, in cooperation with PPG Industries, investigated the performance of a new glass technology, Herculite® XP, for ATFP applications. The program that funded the subject of this report was intended to validate Herculite® XP glass performance and to facilitate its use in window systems meant for commercial availability to installations providing services, training and medical treatment. Since U.S. interests are constantly exposed to the enemy's adapting and escalating threats to defeat current protection systems, the designed systems must provide protection across a broader range of threats that includes blast overload situations.

The failure of window systems in buildings subjected to blast loads causes the majority of injuries in bombing events. Glass shards from monolithic window systems enter a building at velocities sufficient to cause lacerations and injuries. In blast "overload" scenarios, or scenarios where the blast load exceeds the "prescribed" design load per applicable criteria, typical laminated window systems can pull out of frames and fly into occupied spaces. Personnel impacted by these larger and heavier pieces of debris will likely be subject to blunt trauma, potentially resulting in fatality.

Traditional glazing systems designed for blast and impact loads use relatively thick panes of laminated glass for protection to satisfy ATFP criteria. These systems provide protection primarily through the activation of the latent energy absorption capabilities of traditional poly-vinyl butyral (PVB) interlayers that "glue" lites of AN, HS, or FT glass together for normal wind loads, and act as an anti-spall layer to contain window shards generated by blast loads. In these systems, the low-ductility/low-strength glass plays a small role in protection. The Herculite® XP glass technology is produced through a new tempering process that produces higher strength glass that is 10 times stronger than AN glass and 1.5-2 times stronger than FT glass. Herculite® XP glass provides much higher strength such that the glass itself plays a significant role in protection. Laminated systems consisting of Herculite® XP glass can be thinner and lighter while providing identical protection to current systems. Because of its inherent strength, Herculite® XP glass is also able to better resist impact loads in riot and aggressor scenarios where protection is required from forced entry threats.

PEC was engaged under the program to investigate and illustrate the performance of Herculite® XP glass used in standard commercial window configurations and frames for ATFP applications. PEC engineers were tasked with developing a comprehensive test program to evaluate Herculite® XP, overseeing recommended testing of Herculite® XP in punched-window and storefront assemblies using commercial mullion systems, and analyzing data collected to improve analysis tools and make injury predictions.

3. METHODS, ASSUMPTIONS, AND PROCEDURES

PEC performed and oversaw static and dynamic testing of Herculite® XP glass in commercial window frames to evaluate performance when subjected to blast loads. Testing included: static flexural tests of the glass for material property validation data, shock tube testing of IGUs in commercial frames to evaluate dynamic effects and SDOF predictive tools. The set-up for each test series is summarized below.

3.1. Quasi-Static Testing at PEC

PEC performed eight quasi-static tests at the PEC glass test facility in Austin, Texas to confirm that the production run of Herculite® XP glass for the project was of equivalent strength to that of previously supplied glass from PPG Industries. Window specimens with four monolithic glass thicknesses were constructed and subjected to quasi-static loads to generate static load deflection curves (resistance functions) and to determine surface flaw parameters for Herculite® XP glass. Testing was completed using PEC's static test tank and custom mask fabricated for this program.

3.1.1. Test Matrix and Specimen Description

In previous tests, PEC conducted twelve quasi-static tests under sponsorship of PPG Industries. This original test matrix accounted for three test variables: glass size (width and length), fabrication type (monolithic or laminated), and glass thickness. This data is included in Table 1 and is provided with the permission of PPG Industries. The eight tests completed during this program are presented in Table 2.. The main test variable was glass thickness.

Table 1. Original Quasi-Static Test Matrix

Identification		Actual Glass Dim.		Daylight Opening		Glass Thickness			Fab. Type *
Test No.	Window No.	Length (in)	Width (in)	Length (in)	Width (in)	Gross (in)	PVB (in)	Net (in)	
1	1	38.9375	26.9375	37.0625	25.3125	0.186	0	0.186	M
2	2	39.0	27.0	37.0625	25.0	0.19	0	0.19	M
3	3	39.0	27.0	37.0625	25.0	0.164	0	0.164	M
4	4	38.9375	26.9375	37.0	24.8125	0.165	0	0.165	M
5	1	62.9375	33.9375	61.125	31.875	0.159	0	0.159	M
6	2	63.0	33.9375	61.0	32.0	0.149	0	0.149	M
7	3	63.0	33.8125	61.125	32.0	0.225	0	0.225	M
8	4	63.0	33.875	61.0625	31.9375	0.22	0	0.22	M
9	5	63.0	34.0	61.125	32.0	0.372	0.06	0.312	L
10	8	62.9375	33.9375	60.9375	31.9375	0.376	0.06	0.316	L
11	9	63.0	34.0	61.0	32.0	0.374	0.06	0.314	L
12	10	63.0	33.9375	61.0	31.9375	0.376	0.06	0.316	L

* M = Monolithic; L = Laminate

Table 2. New Quasi-Static Test Matrix

Identification		Actual Glass Dim.		Daylight Opening		Glass Thickness			Fab. Type *
Test No.	Window No.	Length (in)	Width (in)	Length (in)	Width (in)	Gross (in)	PVB (in)	Net (in)	
1	1	60	33.875	58.125	32	0.154	0	0.154	M
2	2	60	33.875	58.125	32	0.156	0	0.156	M
3	3	60	33.875	58.125	32	0.124	0	0.124	M
4	4	60	33.875	58.0625	32	0.181	0	0.181	M
5	5	60	33.875	58.125	32	0.187	0	0.187	M
6	6	60	33.875	58.125	32	0.116	0	0.116	M
7	7	60	33.875	58.0625	32	0.221	0	0.221	M
8	8	60	33.875	58.125	32	0.22	0	0.22	M

* M = Monolithic

The nominal glass sizes were 3-ft × 5-ft (width × length), with actual glass dimensions of 34-in × 58-in. All frame pieces were fabricated from 6061-T6 aluminum stock. Figure 1 illustrates the typical connection detail between the glass, aluminum frame, and reaction structure. Note that the glass-to-frame connection utilized a 1-in, 3M VHB Structural Glazing (grey) Tape G23F on both glazing faces. The window frame connections closely simulated fixed boundary conditions due to the rigidity of the aluminum window frame, steel channel, and aluminum shims.

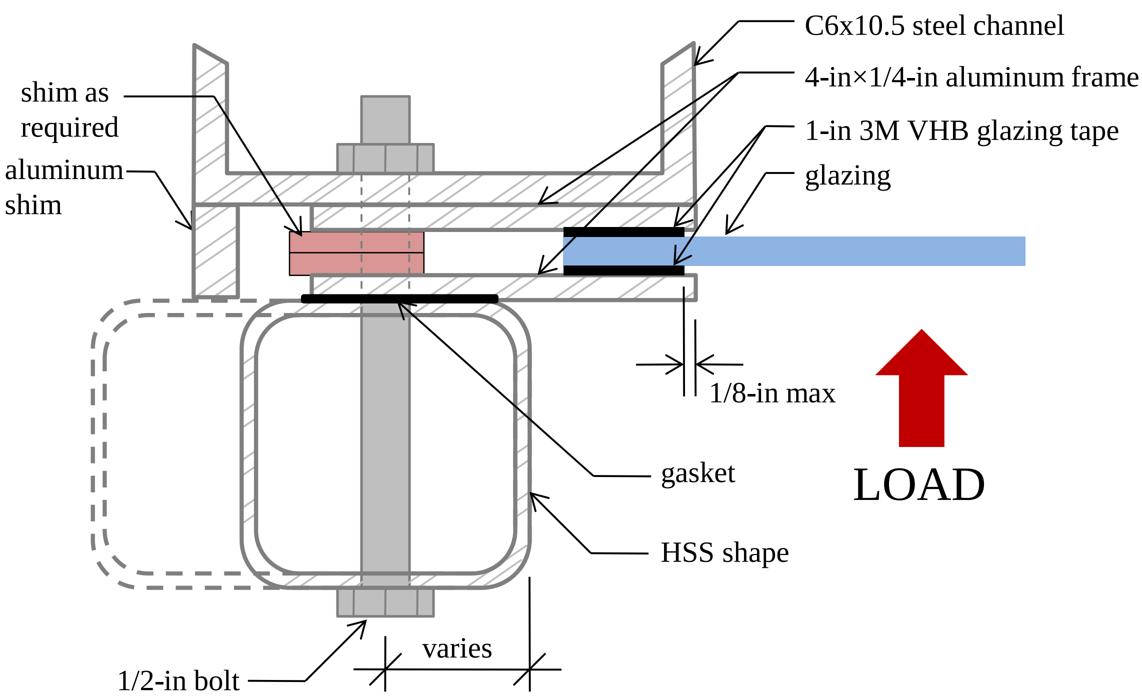

Figure 1. Typical Quasi-Static Frame Connection

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3.1.2. Test Set-up

Eight additional tests on monolithic Herculite® XP glass were performed with the PEC static test tank. Each framed glass lite was attached to the test tank with a steel mask corresponding to the nominal glass size. The tank utilized water to apply a uniform pressure to the glass. The side of the glass facing the inside of the test tank is denoted as the "blast" face and represents the exterior face of a window in a building. For all static testing, PEC used an ultraviolet lamp to determine the tinned (or weak) side of the glass. The tinned side was used as the blast face for all static tests, such that the strong side of the glass was facing up and tested in flexure.

The test tank has a 4-ft × 6-ft opening and is 9-in deep. The mask was bolted to the test tank to decrease the opening to the nominal glass size. The non-responding window frame was bolted to the steel mask as shown in Figure 2. A rubber gasket was placed between the tank/mask and mask/frame interfaces to create a watertight seal. After shimming the frame at each bolt, the bolts were tightened around the frame and tank perimeter to minimize leaks.

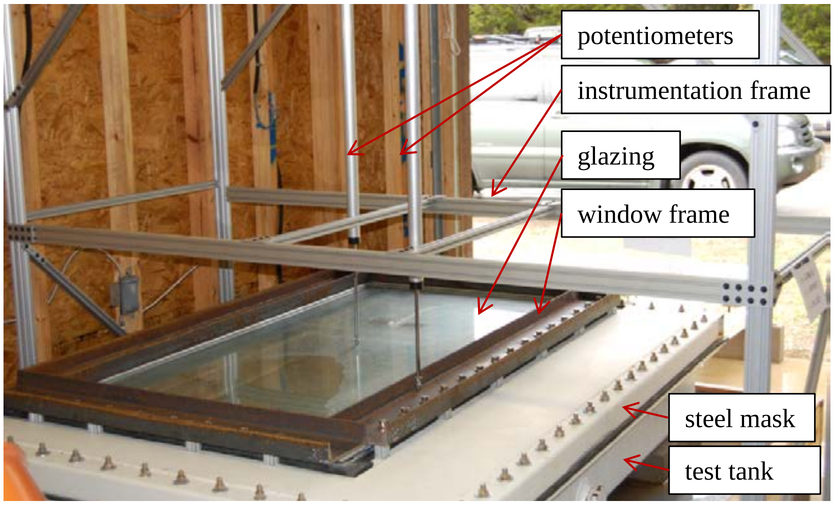


Figure 2. Quasi-Static Test Set-up

3.1.3. Instrumentation

Instrumentation during each test included a pressure gauge and two linear potentiometers. The pressure gauge, mounted on the test tank sidewall, measured the applied water pressure. Each test employed the use of two linear potentiometers (mounted to the instrumentation frame over the test tank) to measure the displacement at the geometric center experienced by the glazing during the applied loading history, as shown in Figure 2, and to measure any support frame displacement and inferred rotation. PEC constructed a custom LabView program to support all data acquisition. In addition, a regular-speed video camera documented each test.

3.2. Shock Tube Testing at ABS

PEC performed 21 shock tube tests at the ABS facility in Bulverde, Texas. ABS was a subconsultant on the project. The goal of the shock tube testing was to evaluate the performance of Herculite® XP glass subjected to dynamic loads (to evaluate performance including rate effects) and evaluate predictive tools for glass response (maximum deflections).

3.2.1. Test Matrix and Specimen Description

ABS performed 21 shock tube tests on Herculite® XP windows in steel or aluminum frames. The nominal glass size was 3-ft × 5-ft (width × length). The main test variables were window layup, frame type, and load, as shown in Table 3. Loads on the windows were varied so as to cause two types of response: “no break” and “just cracked” glass conditions. In addition, some identical tests were performed to evaluate repeatability. Two types of windows were tested: monolithic lites and IGU layups. All glass lites measure 34-in × 60-in while the final daylight opening (DLO) depended on the frame type. All glazing was provided by PPG. The IGUs were delivered to PSLLC for installation into commercial aluminum mullion frames with steel reinforcement. Monolithic lites were installed into steel angle frames by ABS.

Table 3. Summary of Herculite® XP Window Layups

Type	No. of Samples	Window Layup - Nominal Thickness (in)			Frame Type
		Outer Lite	Air Gap	Inner Lite*	
1	4	3/16	1/2	1/4 laminate (0.060 PVB)	aluminum
2	3	1/4	1/2	5/16 laminate (0.060 PVB)	aluminum
3	3	1/4	1/2	3/8 laminate (0.060 PVB)	aluminum
4	4	3/16	1/2	1/4	aluminum
5	1	1/8	-	-	steel
	1	5/32	-	-	steel
	1	3/16	-	-	steel
	1	1/4	-	-	steel

* laminates composed of 2 equivalent thickness lites of glass

The single lites (Type 5) used monolithic glass in a steel frame. The monolithic steel window frame was comprised of nested angles secured to the glass with a 1-in glazing tape connection, as shown in Figure 3. During construction, ABS spot welded the nested angles together to reduce the stress on the glazing tape prior to mounting the window vertically in the shock tube support frame. The steel frame was anchored to the support frame on all four sides.

Four of the layups were IGUs, of which three consisted of a laminated inner pane. The laminated inner panes were assembled with a 0.060-in PVB layer between two lites of equal thickness glass. The outer lite of glass (side closest to the threat or facing inside of shock tube) in all cases was a monolithic piece of Herculite® XP glass. The inner lite (side away from threat or facing out of the shock tube) was either monolithic or laminated. IGU configurations are shown in Table 3. PSLLC provided commercial aluminum frames for all IGU windows extruded from existing dies. The glazing was secured to the frame on all four sides with a 1/2-in bead width of DOW 995 silicone as shown in Figure 4. A neoprene gasket was placed between the mullion cap and the outer pane. A 1/4-in × 2-3/4-in steel insert was placed along the outside wall of the mullions and bolted to the test frame with 5/8-in diameter A325 bolts at 12-in on center (except in the corners where a 3/4-in diameter A490 bolt was required). The inserts where bent at the ends to create a shear block into the head/sill members. Aluminum frames were attached to the support frame along the jambs only (unsupported head/sill members spanned between jambs).

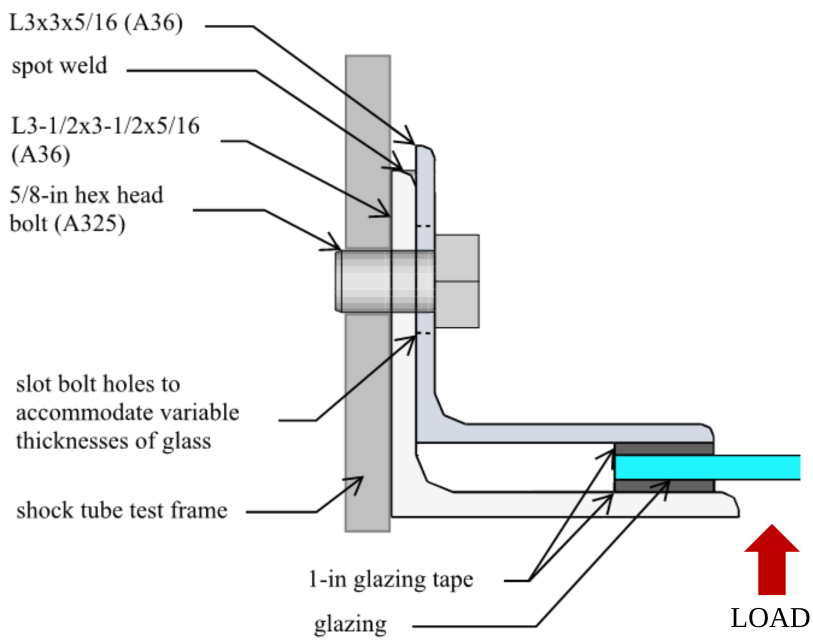


Figure 3. Typical Shock Tube Window Connection: Single Lite Layup

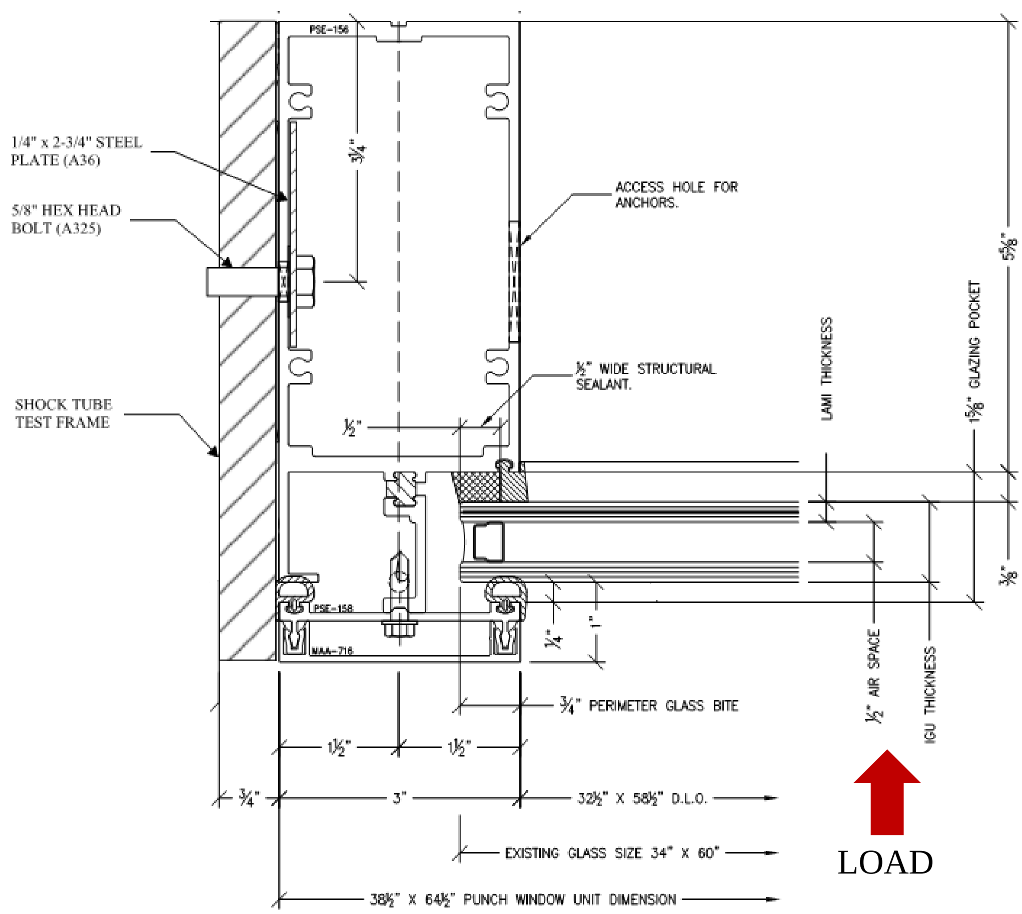


Figure 4. Typical Shock Tube Window Connection: IGU Layup

3.2.2. Test Set-up

Testing was conducted with the ABS shock tube in Bulverde, Texas. ABS provided a window support frame to reduce the shock tube opening and provide connection points for both types of window frames. The window support frame is shown in Figure 5. The support frame was designed to connect to the second-to-last cone section of the shock tube. The shortened cone was used to reach higher window loads. ABS was able to reach peak pressures near 30 psi and peak impulses near 300 psi-ms by removing the last cone section. However, in generating the high pressures necessary to fracture the window, control of the resulting impulses was difficult such that the applied impulse exceeded the planned impulse in many cases.

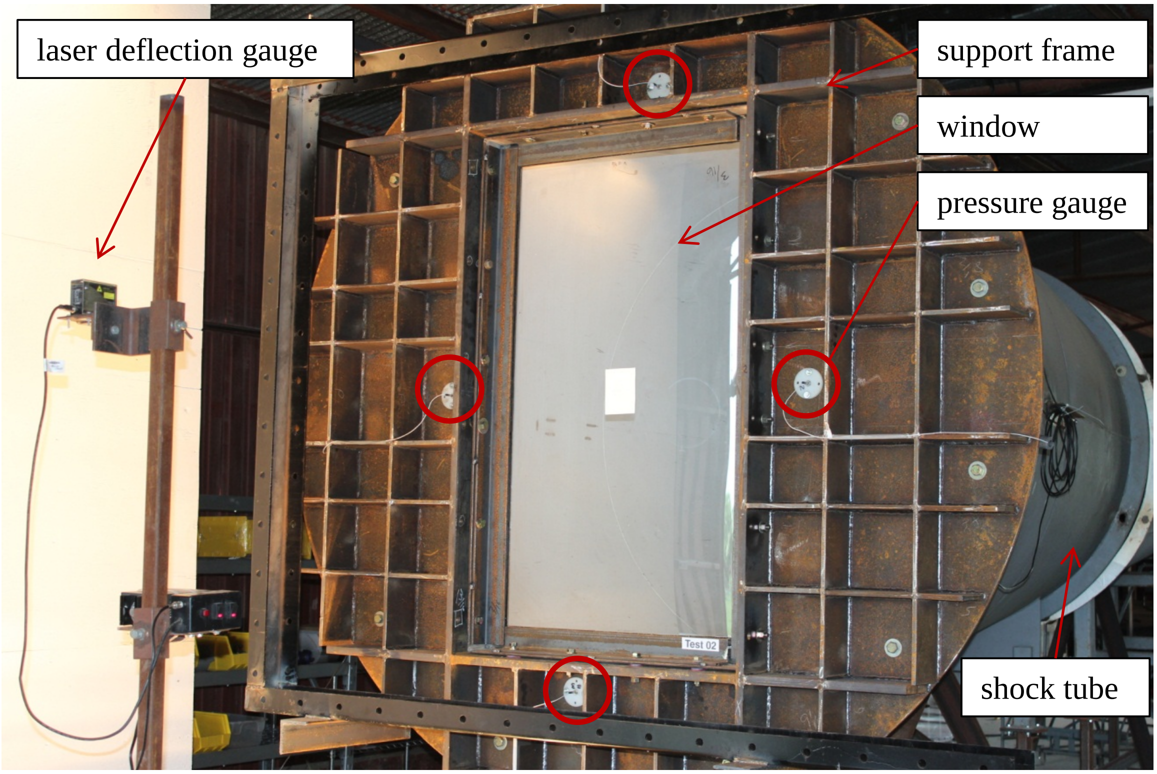


Figure 5. Shock Tube Test Set-up

3.2.3. Instrumentation

Instrumentation used during the shock tube tests included four pressure gauges, two laser deflection gauges, three high-speed video cameras, digital image correlation (DIC), and pre- and post-test pictures. ABS collected and processed all data except DIC which was processed and shard velocity data which was processed by PEC.

Four reflected pressure gauges were located within the same plane as the test specimens (along the horizontal and vertical centerlines) on the inside face of the shock tube frame constructed by ABS, as shown in Figure 5. PEC averaged all four pressure histories collected to determine the final load. Very little negative phase was observed due to the required shock tube setup (no gaps and shortened cone).

Two laser deflection gauges were used during each test to capture displacement of both IGU lites, as shown in Figure 5. Reflective stickers were placed along the vertical and horizontal centerlines for each sample within a 6-in radius of the center of the window, where maximum displacement occurred. However, most tests were conducted using only one laser gauge which captured data on the inner lite only, as one laser gauge was damaged by debris during a test.

To document the tests visually, one high-speed video camera was positioned behind and off center from the inner face of the test sample at approximately 45 degrees, as shown in Figure 6. A second set of high-speed video cameras were added to track fragment velocities when conducting monolithic lite and non-laminated IGU debris tests. A wood frame with a 4-in wide slit was placed behind the window to transform the debris cloud into a narrow band of debris that could be captured by a high-speed video camera shooting orthogonal to the debris path. The slit was oriented in the vertical direction to capture the distribution along the long span of the glass. Lighting was the most important part of the video imaging effort, as insufficient contrast between the fragments and the backdrop could cause problems identifying fragments. Several high-wattage flood lamps were used to illuminate the backdrop of the video. When the debris tracking was not conducted, the second set of cameras was repurposed for DIC data collection directly behind the shock tube. The DIC setup required a black and white (high-contrast) speckle pattern to be applied to the back of the specimen and for the specimen to be well-lit with high-wattage flood lamps.

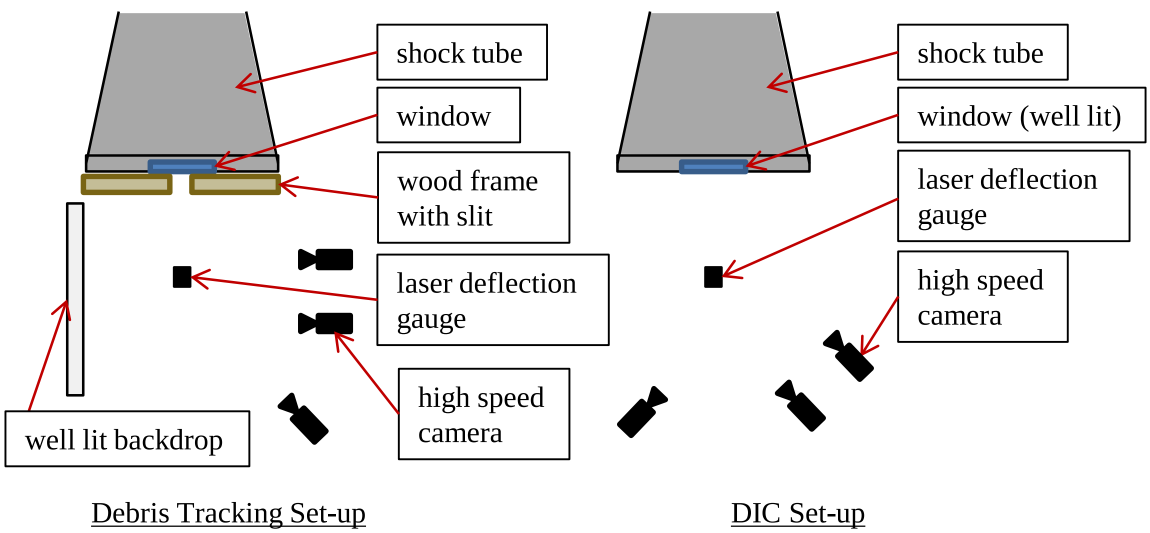


Figure 6. Shock Tube Instrumentation Set-up

4. RESULTS

PEC performed and oversaw static and dynamic testing of Herculite® XP glass in commercial frames to evaluate performance when subjected to blast loads. Testing included: static flexural tests of the glass for material property validation data, shock tube testing of IGUs in commercial frames to evaluate dynamic effects and SDOF predictive tools. The results from each test series are summarized below.

4.1. Quasi-Static Testing at PEC

Results from quasi-static tests on Herculite® XP glass from the PPG test series and the additional eight tests are summarized in Table 4 and Table 5, respectively.

Table 4. Original Quasi-Static Test Results Summary

Test No.	Nominal Window Size* (ft)	Gross Thick -ness (in)	Glass Break				Max Polymer Failure	
			Pressure (psi)	Mid Point Defl. (in)	Frame Defl. (in)	Net Defl. (in)	Pressure (psi)	Mid Point Defl. (in)
1	2 × 3 M	0.186	17.4	2.21	0.94	1.27	-	-
2	2 × 3 M	0.19	15.0	1.96	0.84	1.12	-	-
3	2 × 3 M	0.164	11.2	1.78	0.59	1.19	-	-
4	2 × 3 M	0.165	8.9	1.51	0.48	1.03	-	-
5	3 × 5 M	0.159	4.9	2.10	0.15	1.95	-	-
6	3 × 5 M	0.149	5.3	2.24	0.25	1.99	-	-
7	3 × 5 M	0.225	9.6	2.52	0.28	2.24	-	-
8	3 × 5 M	0.22	9.7	2.45	0.53	1.92	-	-
9	3 × 5 L	0.372	10.0	2.12	0.25	1.87	2.30	16.34
10	3 × 5 L	0.376	10.3	2.13	0.17	1.96	1.59	11.63
11	3 × 5 L	0.374	10.1	2.16	0.20	1.97	1.59	12.57
12	3 × 5 L	0.376	10.0	2.01	0.19	1.82	1.72	14.68

* M = Monolithic; L = Laminate with 0.060-in PVB

Table 5. New Quasi-Static Test Results Summary

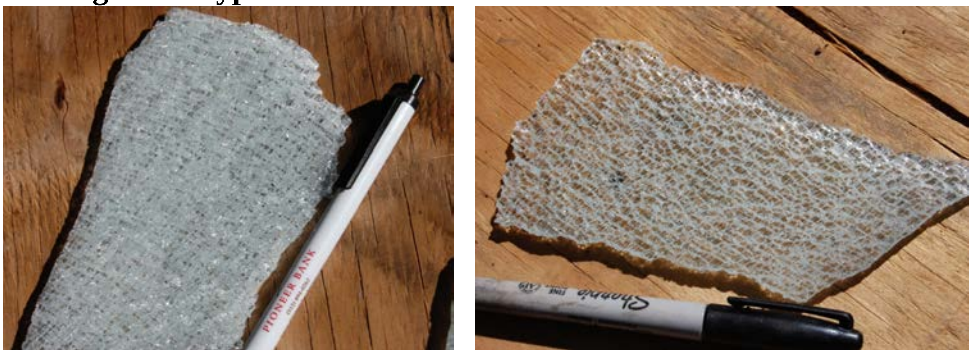
Test No.	Nominal Window Size* (ft)	Gross Thickness (in)	Glass Break Pressure (psi)	Glass Break Mid Point Defl. (in)	Glass Break Frame Defl. (in)	Glass Break Net Defl. (in)
1	3 × 5 M	0.154	5.9	2.05	0.11	1.94
2	3 × 5 M	0.156	6.9	2.20	0.14	2.06
3	3 × 5 M	0.124	4.0	2.01	0.09	1.93
4	3 × 5 M	0.181	7.0	2.01	0.13	1.87
5	3 × 5 M	0.187	8.3	2.16	0.16	2.00
6	3 × 5 M	0.116	5.1	2.20	0.11	2.09
7	3 × 5 M	0.221	12.9	2.20	0.20	2.00
8	3 × 5 M	0.22	10.7	2.14	0.18	1.95

* M = Monolithic

4.1.1. Test Observations

The residual stress "trapped" in the glass after tempering effectively reduces the apparent surface flaws. This enabled the Herculite® XP glass to reach high glass failure pressures relative to AN and FT glass. In addition, all of the specimens exhibited a relatively explosive glass failure due to the residual stored energy from tempering and the applied strain energy accumulated during the quasi-static testing. Unlike the failure of AN glass, the monolithic Herculite® XP glass exhibited micro cracking, as shown in Figure 7. In general, the fracture planes of the glass fragments were dull and relatively smooth. The primary mode of failure was brittle fracture precipitated by stress concentration at the critical surface flaw site. Upon failure, monolithic Herculite® XP specimens tended to fracture all the way up to the glazing tape bite at the aluminum frame edges.

Figure 7. Typical Monolithic Herculite® XP Fracture Patterns



4.1.2. Recommended SDOF Parameters

The pressure and displacement histories from each test were used to develop static resistance functions, for each test specimen. The measured gauge pressure inside the tank was taken to be equivalent to the resistance of the window assembly. Prior to each test, the pressure gauge was corrected for the additional pressure afforded by the static head of the water inside the tank.

The results of the quasi-static tests were used to confirm the Glass Failure Prediction Model (GFPM) parameters for Herculite® XP glazing. The GFPM is based on the theory that glass plate failure is a result of glass surface flaw interaction and surface tensile stresses induced by externally applied forces. The two surface flaw parameters m and k quantitatively represent the severity and distribution of surface flaws. The previous Herculite® XP static test results were used to determine the surface flaw parameters, $m = 6.44$ and $k = 2.86 \times 10^{-53} N^{-7} m^{12}$. New test results yielded $m = 6.34$ showing that the predicted values are consistently conservative (i.e., if new $m < 6.44$, then predicted resistance using $m = 6.44$ was less than the resistance measured during testing, typically by around 10%). Therefore the current batch of Herculite® XP glass was comparable in strength to the previous batch of Herculite® XP glass tested and a new m of 6.40 was selected for shock tube test predictions.

4.2. Shock Tube Testing at ABS

Results from the 21 shock tube tests on Herculite® XP windows are summarized in Table 6 and Table 7. Loads, deflections, and glass temperatures were used to evaluate the SDOF analysis parameters used to make response predictions.

Overall, the shock tube testing provided an abundance of data with regard to deformed shape, debris fly-out, crack propagation, glass deflection at failure, and PVB bite considerations. Initial predictions by SBEDS-W (Single degree of freedom Blast Effects Design Spreadsheet for Windows) did a reasonable job of predicting glass response. The data obtained from the high-speed cameras for DIC analysis was used to capture crack propagation and deformed shape, which was used to better map the stress state of the glass at failure and improve the predictive capabilities of the GFPM found in SBEDS-W.

Table 6. Shock Tube Test Results Summary—Shard Velocities

Test No.	Window Type	Load Information		Glass Break Time (ms)		Shard Velocities	
		Peak Pressure (psi)	Peak Impulse (psi-ms)	Outer Lite	Inner Lite	Max. (ft/s)	Aver. (ft/s)
3	5 - 3/16	8.8	43.2	N/A	break	20	20
5	4	20.3	147.7	6.5[1,2] ± 1	7.5[2] ± 1	92	82
8	5 - 1/4	19.8	140.3	N/A	5.3[1,2] ± 1	182	154
16	5 - 1/8	9.0	27.8	N/A	5.5[1] ± 0.5	77	74
17	5 - 5/32	9.0	31.9	N/A	6[1] ± 0.5	116	105
18	5 - 1/4	15.1	172.6	N/A	5[1] ± 0.5	231	221

Notes: [1]ABS Estimation; [2]High-Speed Video Estimation; N/A - Not Applicable

Table 7. Shock Tube Test Results Summary—Deflections

Test No.	Window Type	Load Information		Outer Lite	Inner Lite				
		Peak Pressure (psi)	Peak Impulse (psi-ms)	Glass Break Time (ms)	Glass Break Time (ms)	Max. Deflection (in)	Time of Max. Defl. (ms)	PVB Bite Failure	Glass Temp (°F)
1	5 - 1/4	9.0	46.5	N/A	7.7[1,2] ± 1	2.14 - 2.45[a]	7.7[1,2] ± 1	N/A	88
2	5 - 3/16	6.5	15.4	N/A	no break	1.42[a]	6.48 ± 1	N/A	91
3	5 - 3/16	8.8	43.2	N/A	break	1.92[a]	6.9 ± 1	N/A	89
4	4	19.2	149.7	7.2[1,2] ± 1	8.2[1,2] ± 1	3.13 - 3.92[a]	8.2[1,2] ± 1	N/A	80
5	4	20.3	147.7	6.5[1,2] ± 1	7.5[2] ± 1	3.42 - 4.62[a]	7.5[2] ± 1	N/A	84
6	4	15.1	128.9	9.5[1,2] ± 1	no break	2.57[a]	7.67 ± 2	N/A	87
7	4	18.0	166.2	8.5[1,2] ± 1	no break	2.62[a]	8.88 ± 1	N/A	85
8	5 - 1/4	19.8	140.3	N/A	5.3[1,2] ± 1	2.71 - 6.10[a]	5.3[1,2] ± 1	N/A	86
9	1	19.9	145.5	6.1[2] ± 0.15	6.1[2] ± 0.15	2.67[b]	6.1[2] ± 0.15	40%	>130
10	1	18.0	140.9	N/M	7.2[2] ± 0.15	2.40[b]	7.2[2] ± 0.15	27%	95
11	1	15.3	132.5	no break	no break	2.37[a]	8.57 ± 1	none	92
12	1	16.6	151.8	no break	no break	2.55[b]	7.80 ± 0.15	none	89
13	1	19.5	159.5	N/M	6.2[2] ± 0.15	2.44[b]	6.2[2] ± 0.15	48%	88
14	3	24.1	196.9	no break	no break	2.51[b]	7.50 ± 0.15	none	93
15	3	28.8	292.2	N/M	<6.7[2] ± 0.5	N/M	N/M	96%	96
16	5 - 1/8	9.0	27.8	N/A	5.5[1] ± 0.5	1.67 - 3.08[a]	5.5[1] ± 0.5	N/A	69
17	5 - 5/32	9.0	31.9	N/A	6[1] ± 0.5	2.23 - 4.40[a]	6[1] ± 0.5	N/A	74
18	5 - 1/4	15.1	172.6	N/A	5[1] ± 0.5	1.03 - 3.58[a]	5[1] ± 0.5	N/A	79
19	2	25.1	164.3	no break	no break	2.58[a]	7.65 ± 1.5	none	86
20	2	28.1	165.5	no break	no break	2.60[a]	7.87 ± 1.5	none	87
21	2	29.2	145.8	no break	no break	2.77[a]	6.71 ± 1.5	none	88

Notes: [1]ABS Estimation; [2]High-Speed Video Estimation; [a]Laser Deflection; [b]DIC Deflection
N/A - Not Applicable; N/M - Not Measured

4.2.1. Window Response Observations

4.2.1.1. Deformed Glass Shape

The team utilized DIC software to capture the maximum deflection and deformed shape of the glass prior to breakage under dynamic loading. The imaging software tracked a speckled pattern of black dots over a white surface from the vantage point of two cameras. With two cameras watching the speckle pattern, the images were combined to calculate deformation (out-of-plane motion) and provide strain distributions (in-plane motion) across each piece of glazing.

In general, the maximum deflection measured in the DIC data matched the laser deflection data. However, the trigger timing was typically earlier due to the increased frame rate of the high-speed cameras over the laser gauge. The different sampling rates caused a discrepancy between the timing of the measured results. To compare the results better, the laser gauge data was adjusted to match the higher resolution DIC results. Additionally, due to the higher frame rate used on these cameras, crack propagation was viewable on Test 9. In general, cracks began in the corners and progressed throughout the glazing. The propagation of fracture from the corners to the center of the glass occurred in approximately 1 ms in the tests. Thus onset of cracking of windows without viewable corners due to the speckle pattern could be estimated.

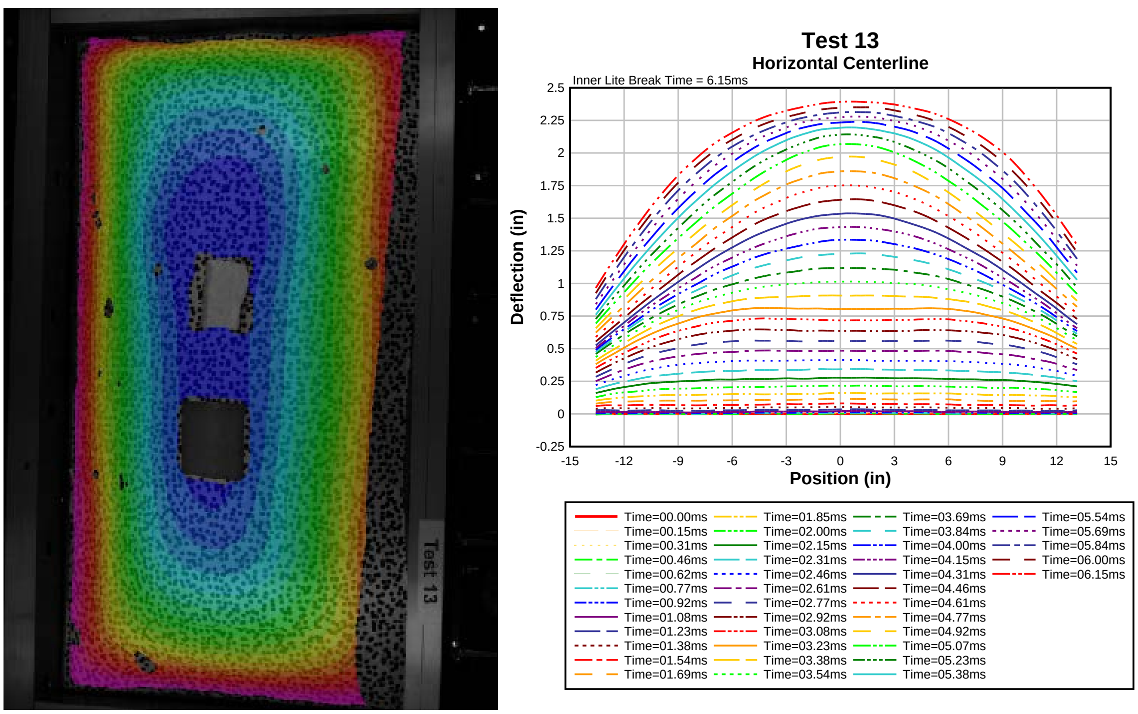


Figure 8. Shock Tube Test 13 Results: DIC Deflection Data

4.2.1.2. PVB Bite Observations

When testing the laminated IGU layups, several issues arose with the PVB that contributed to a decrease in overall resistance. Test 9 was the first test where DIC was performed. Two 2-kilowatt lights mounted near the top and bottom of the window were required to sufficiently illuminate the speckle pattern. The heat generated from these lights was estimated to have increased the temperature of the inner lite (laminate) above 130 °F. This temperature increase likely greatly decreased the shear capacity of the PVB and caused the laminated glass to behave more like a stacked plate instead of a composite cross section. The high temperature led to premature failure of the window and was accounted for in analyses by adjustment of the PVB lamination factor. Subsequent tests with DIC mitigated the PVB degradation by limiting the time the lights were switched on, by increasing the offset of the lights from the window and by using fans to blow cool air onto the window. The ambient air temperature was still reasonably high for all tests (86–96 °F) relative to a typical conditioned indoor space (around 76 °F).

4.2.1.3. Frame and Mullion Response

The steel frame and aluminum mullions exhibited very little permanent deformation when evaluated after the tests. The only evidence of deformation was found in the aluminum mullions near the shear block where the head and sill members induced rotation at the connections with the rigidly attached jambs. This was only found on the thicker IGU windows (Type 2 and 3), upon which the connection design was based. It appears that little to no plastic deformation was found in the head and sill members (the jambs were continuously supported and did not participate in flexural response. However, a slight “racking” or “skew” of the jambs was noted after a couple of the high load tests.

4.2.2. SDOF Analysis Comparison

The initial monolithic glass tests were performed to investigate rate effects included in the GFPM model (see Section 4.1.2 for additional background information on the GFPM model). Shock tube test results and predictions using an m of 6.4 in SBEDS-W are summarized in Table 8. SBEDS-W predicted slightly higher deflections and resistances to first crack than observed in the tests. Additionally, the break point of glass was predicted correctly 57% of the time based on flaw parameters determined from static testing. Using the dynamic test data, m was adjusted to 6.55 to account for these differences which were most likely due to rate effects and assumed deformed shape. Figure 9 illustrates the effect of inertia on the observed test data versus the idealized window response calculated by SDOF calculations in SBEDS-W.

Table 8. Shock Tube Results: Window Type 5 Comparisons

Test No.	Glass Thickness (in)	Measured Results		SBEDS-W Predictions	
		Glass Break Time (ms)	Max. Defl. (in)	Glass Break Time (ms)	Max. Defl. (in)
1	1/4	7.7[1,2] ± 1	2.14 - 2.45[a]	no break	2.33
2	3/16	no break	1.42[a]	no break	1.54
3	3/16	break	1.92[a]	no break	2.67
8	1/4	5.3[1,2] ± 1	2.71 - 6.10[a]	4.15	2.98
16	1/8	5.5[1] ± 0.5	1.67 - 3.08[a]	5.17	2.82
17	5/32	6[1] ± 0.5	2.23 - 4.40[a]	no break	2.81
18	1/4	5[1] ± 0.5	1.03 - 3.58[a]	4.94	2.99

Notes: [1]ABS Estimation; [2]High-Speed Video Estimation
[a]Laser Deflection

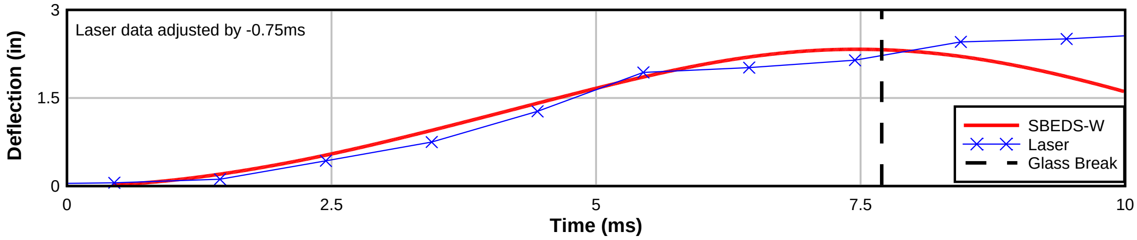


Figure 9. Shock Tube Test 1 Results: Deflection Comparison

In addition to the monolithic glass tests, several laminated IGU layups were tested. The shock tube pressure capacity was the limiting factor on the thicker glass layups (Type 2 and 3) as higher pressures were needed to break the glass without subsequent over loading of the PVB. Higher impulses with lower pressures could be achieved to break the glass, but this resulted in a lack of control in the testing and caused PVB failure and catastrophic failure of the system, immediately after glass break occurred. Several successful and controlled tests were conducted. Table 9 shows the inner lite test results and the corresponding SBEDS-W predictions using an *m* of 6.4. On average, SBEDS-W was 3% lower than the measured deflections of the inner lite when the glass did not break (see Figure 10). Thus, deformed shape has a limited effect on the maximum deflection of the window at midspan, which occurs after the shape has returned to the typical parabolic shape. However, the GFPM predicted no failure for each of the tests where the glass failed, which could be improved. Using the dynamic test data, *m* was adjusted to 6.55 to account for these differences which were most likely due to rate effects.

Table 9. Shock Tube Results: Laminated IGU Comparisons

Test No.	Window Type	Measured Results		SBEDS-W Predictions		SBEDS-W Error (%)
		Glass Break Time (ms)	Max. Defl. Inner Lite (in)	Glass Break Time (ms)	Max. Defl. Inner Lite (in)	
9	1	6.1[2] ± 0.15	2.67[b]	no break	2.77	3.7%
10	1	7.2[2] ± 0.15	2.40[b]	no break	2.5	4.2%
11	1	no break	2.37[a]	no break	2.23	-5.9%
12	1	no break	2.55[b]	no break	2.42	-5.1%
13	1	6.2[2] ± 0.15	2.44[b]	no break	2.76	13.1%
14	3	no break	2.51[b]	no break	2.45	-2.4%
15	3	<6.7[2] ± 0.5	N/M	no break	2.9	N/M
19	2	no break	2.58[a]	no break	2.58	0.0%
20	2	no break	2.60[a]	no break	2.58	-0.8%
21	2	no break	2.77[a]	no break	2.66	-4.0%

Notes: [1]ABS Estimation; [2]High-Speed Video Estimation
[a]Laser Deflection; [b]DIC Deflection; N/M - not measured

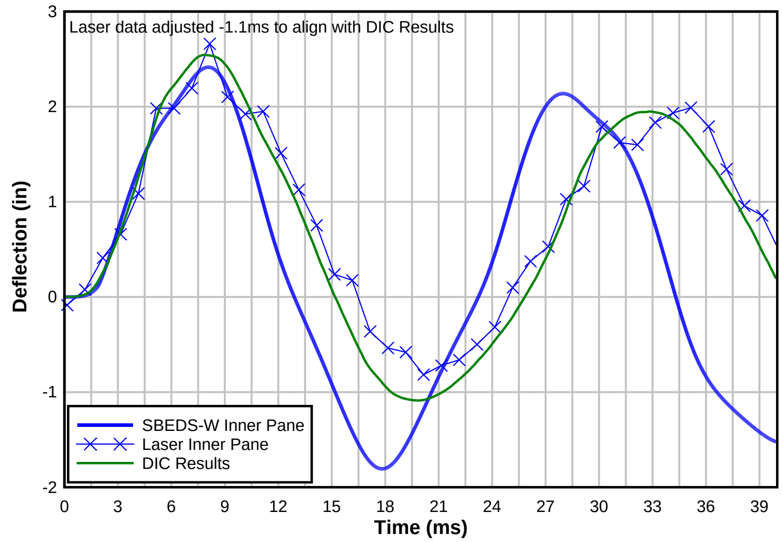


Figure 10. Shock Tube Test 12 Results: Deflection Comparison

5. DISCUSSION

Upon completion of the tasked work under this contract, PEC has performed a review of the static and dynamic test data, flexural model predictions, and injury predictions for Herculite® XP glazing. The data collected during this program was used to improve design tools for glazing and mullions, and develop a preliminary design approach for Herculite® XP.

5.1. Predictability of Herculite® XP Glazing Performance Subjected to Blast Loads

Testing during this program provided sufficient data to evaluate a resistance function for Herculite® XP IGUs for use in a dynamic SDOF analysis program. Comparisons of test data illustrate that the model can conservatively predict the performance of Herculite® XP IGUs subjected to blast loads. In general, Herculite® XP can provide the same level of protection as AN or HS glazing using a thinner and lighter section.

5.1.1. Overall Glazing Performance

As shown in the blast tests, the Herculite® XP glass performs well when subjected to blast loads. The glass has a high strength before fracture and fails into small, relatively smooth-edged fragments.

5.1.1.1. Deformed Shape

DIC data obtained from shock tube tests in Section 4.2.1.1 allowed PEC to verify the deformed shape of the window during dynamic response. The deformed shape affects the assumed load-mass factor in SDOF and can alter the predicted response of the system. DIC revealed the typical parabolic shape forms quickly after the onset of the blast load. Since glass fracture occurred after this transition in deformed shape, the assumed load-mass factors in SBEDS-W are valid and provided predictions that match observed test results. This deformed shape was validated by DIC data.

5.1.1.2. IGU response

IGUs were tested in both the shock tube and blast tests. The IGUs consisted of both monolithic glass on the outer lite and either monolithic or laminated glass on the inner lite. The apparent difference between monolithic and laminated glass as the inner lite showed little difference as long as the temperature of the glass remained low. The effect of temperature on PVB on laminated glass strength is beyond the scope of this project and was not investigated further. However, the temperature appeared to have minimal effect as long as the temperature remained below 100 °F.

The shock tube and blast tests also revealed a dependency on pressure/impulse characteristics of the blast load on the glass. Due to limitations from the shock tube, higher pressures were unattainable and higher impulses were required to break the glass. However, the additional impulse caused the PVB laminate to tear soon after the glass failed creating an extreme overload scenario for relatively low pressures. This phenomenon was not observed in the blast tests where relatively high pressures were achieved as expected in conjunction with lower impulses. The blast test specimens (if failure occurred) did not tear through the PVB laminate. This was replicated in the SDOF predictions and can be accounted for by analyzing the inertia and remaining blast load at glass failure through dynamic analysis.

5.1.2. Accuracy of SDOF Analysis Predictions - Glazing

Shock tube and blast testing results correlated with SDOF predictions made with SBEDS-W. As discussed previously, the deformed shape of the glass is consistent with large deformation plate theory and exhibits a parabolic shape soon after load is applied. Additionally, the resistance curve generated with the polynomial method found in Appendix X2 in ASTM E1300 correlates to resistance functions measured during static testing.

Lastly, the modifications to GFPM used in SBEDS-W conservatively predict glass failure. The flaw parameters were calibrated to static and shock tube test data and accurately predicted glass failure in the final blast tests. Comparisons with test data are discussed further in Section 5.3.

5.1.3. Final Design Parameters and Assumptions

The flaw parameters for the SBEDS-W GFPM model were refined throughout the course of this project. The modified GFPM treats the flaw parameter, *k*, as a constant (k = 2.86e-53$N^{-7}m^{12}$) and must be run using SI units. For the remaining flaw parameter, *m*, a value of 6.34 was selected to match quasi-static test results. However, for short duration loads such as shock tube and blast tests, a *m* of 6.55 was selected to match test results. Since an *m* value of 6.55 is conservative for all load durations and calibrated to blast loads, it is the final design value selected for Herculite® XP for use in the SBEDS-W modified GFPM, as shown in Table 10. The SBEDS-W model assumes that a probability of 0.5 will be used for design purposes. Additionally, while only a single glazing geometry was tested and evaluated in the shock tube and blast tests, size variation was evaluated as a part of the original static test series and not found to change the design parameters significantly. Window sizes significantly larger than 60-in by 34-in tested could require additional investigation, but should be adequately predicted for aggregate response using the parameters recommended.

Table 10. Recommended Flaw Parameters for SBEDS-W GFPM Model

Glass Type	Strength (psi)	Surface Flaw Parameters		Young's Modulus (psi)
		m (for design)	k ($N^{-7} m^{12}$)	
Annealed	3380	7	2.86×10^{-53}	1.04×10^{7}
Heat Strengthened	6750	6.93	2.86×10^{-53}	1.04×10^{7}
Fully Tempered	13500	6.85	2.86×10^{-53}	1.04×10^{7}
Herculite® XP	34000	6.55	2.86×10^{-53}	1.04×10^{7}

A modified approach using the GFPM model for glass selection for static and static equivalent design approaches is discussed in Section 5.3. This modified approach would be used with overall approaches for high-strength glass under consideration as an appendix to ASTM E1300. Under that model, significantly different flaw parameters would be used (m=3, k=3.3e-15$lb^{-3}in^{4}$) for static selection and static equivalent design for wind loads and blast (ASTM F2248 3-second load approaches).

5.2. Response of Commercial Framing System

Based on the results of this test program, Herculite® XP can be successfully used in existing commercial mullion systems to resist blast loads. Data collected provided a better understanding of the composite response of IGUs and mullion. Specifically, the blast test data will allow for development of a MDOF model of glass and mullion system.

5.2.1. Overall System Performance

Shock tube and blast test results showed adequate performance, per response criteria defined in PDC-TR 06-08 of Herculite® XP framed with conventional commercial mullion systems. Shock tube test specimens were mounted along the jambs, which revealed possible difficulties in the ability of the bite to hold on to the glass. However, this was more a function of the large deflections attainable by the Herculite® XP glass (as compared to lower strength AN glass). At high deflections, the glass boundary can constrict considerably, which increases the bite requirements for Herculite® XP. As a result of the shock tube tests, the bite was increased from 0.5-in to 0.75-in for the blast test mullion systems. Minimal bite failures were observed in the blast tests. Thus, this minor design change performed well in the blast tests and should not cause significant limitations to mullion selection.

5.2.1.1. Glass Response

Glass response was not affected significantly by the mullion system, especially for punched windows where the mullions were quite stiff due to the short 5.4-ft span. The storefront vertical mullions spanned 10.5-ft and were much more flexible. However, glass response is dependent on the blast load and phasing of the mullion and glass response In blast test 1, all glass in the storefront systems did not break, which is possibly due to the flexibility of the mullions. Coupling of the mullion and glass response is discussed further in the next section.

5.2.1.2. Mullion Response

Mullions responded similar to predictions made using SDOF with the load applied through the tributary area. However, the mullions formed a hinge at midspan during inbound response which is not accounted for in the SDOF analysis. The formation of the hinge would likely have occurred without the cutouts for the horizontal mullions at midspan, but the cutouts caused stress concentrations to form at the critical section of the mullion and likely accelerated the formation of the hinge

5.2.1.3. Coupled vs. Uncoupled Response

One of the questions surrounding SDOF analysis of storefront and curtain wall systems is the effect of coupling between the glass and mullion responses. When evaluating the glass response, a common and conservative design assumption is perfectly rigid supports. However, this assumption is not true if the mullion experiences significant displacement during the glass response. Likewise, the mullions will receive less load due to the deformation of the glass absorbing some the energy.

At this point it appears the coupled response has a minimal effect on the glazing and mullion response when analyzed with a SDOF program. In blast test 1 and 2, the windows responded much faster than the mullions which essentially decouples the two responses. The glass reached peak displacement before the mullions were able to respond significantly. Consequently, the stiff response from the Herculite® XP resulted in little dissipation of energy prior to mullion response and simple tributary area assumptions yielded good results for SDOF analysis of the mullions.

However, this may not be true for all loads. Low-pressure/high-impulse load combinations may cause the windows and mullion response to be in phase and result in a more coupled response. To analyze a fully coupled system, a more complicated analysis with FEA or MDOF program is required. For the cases tested in this program, a MDOF model seems unnecessary; however, more work should be done in this area to quantify limits for uncoupled assumptions.

5.2.2. Accuracy of SDOF Analysis Predictions - Mullions

Due to the uncoupled performance of the mullion systems, SDOF accurately predicts mullion response for both punched and storefront configurations. With typical support conditions (simply supported) and typical deformed shapes, the predictions were accurate for both blast tests. However, it should be noted that mullion rupture at the midspan was not accounted for in the SDOF analysis, and altered the deformed shape of the mullion by creating a hinge at midspan. Despite this difference, the SDOF predictions showed close correlation to the test results and the maximum deflections used to determine rotation and ductility for design limitations.

5.2.3. Evaluation of Existing Response Criteria

The PDC TR 10-02 (USACE, 2012) defines response criteria for aluminum mullions as a support rotation of 6 degrees and ductility of 7 for a low level of protection (LLOP) response. A LLOP response is defined in the PDC TR 06-08 (USACE, 2008) as heavy damage for secondary components. Heavy damage is defined as a component that “has not failed, but it has significant permanent deformations causing it to be unrepairable”.

Support rotations up to 11.4 degrees were observed in vertical mullions, where a low level of protection was easily met. Thus, the response criteria proposed by the PDC are conservative for mullions used in window assemblies with Herculite® XP glazing. However, again it should be noted that a support rotation of 11.4 degrees was only attained by formation of a hinge at midspan and was potentially near failure of the mullion. Therefore, a higher support rotation may be applicable for storefront systems using Herculite® XP glass, however additional FEA or testing may be required to determine what value is appropriate. Ductility also needs to be accounted for as the formation of a hinge suggests that the response was significantly past the yield deflection.

5.3. Incorporation of Herculite® XP into Industry Standards

In addition to evaluation of Herculite glazing through testing for blast and the evaluation of existing techniques for prediction of that response, a goal of the project was to determine a design method to enable engineers to specify Herculite® XP for windows using consensus-based standards such as ASTM E1300. Herculite® XP glass can be incorporated into existing industry standards, such as ASTM E1300, using an approach outlined by the ASTM task group with minor modifications. Data collected during the test program was used to adjust the approach specifically for Herculite® XP applications. A full design example is provided and includes all design assumptions.

5.3.1. Proposed ASTM E1300 Approach

During the course of this project, the ASTM E1300 committee began discussion of an appendix to the current ASTM E1300 that accommodates higher-strength glass. The new approach extends the original ASTM approach by incorporating the residual compressive surface stress (RCSS) found in higher-strength glass into the material model found in the GFPM.

The original GFPM, developed by Beason and Morgan (1984), was developed through the analysis and testing of AN glass. To summarize the basic premise, the GFPM utilizes a finite difference model (Vallabahn and Wang, 1981) to correlate the lateral pressure on a given piece of glass to its stress distribution. The stress is then modified to account for load duration and biaxiality, which is referenced as the equivalent stress. The equivalent stress is applied to a Weibull distribution where empirical flaw parameters (*m*, *k*) define the shape of the Weibull distribution and correlate equivalent stress to the probability of failure. For more information on the GFPM, please reference Beason and Morgan (1984).

Morse and Norville (2012) took the existing GFPM and modified it to account for the RCSS that is present in HS and FT glass. This is executed by subtracting the RCSS from the stress observed from the finite difference model prior to calculating the equivalent stress in the original GFPM, as shown in Figure 11.

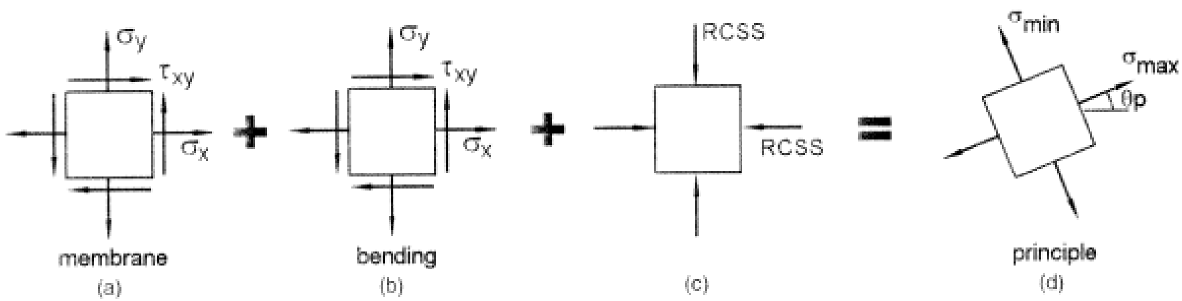


Figure 11. State of Stress Summation (Morse and Norville, 2012)

This approach allows for the same flaw parameters (*m*, *k*) to be used with HS and FT glass under the assumption that the number and distribution of the flaws are identical to AN glass.

This approach on modifying the GFPM differs from the approach recommended in the sections above for dynamic analysis using the GFPM implementation in SBEDS-W, but both yield conservative results when calibrated to blast test data.

5.3.2. Required Adjustments for Herculite® XP

To accommodate the use of Herculite® XP into the proposed ASTM E1300 approach, static and blast data were used to calibrate the modified model. As opposed to AN, HS, and FT glass, Herculite® XP appears to have a different Weibull distribution, and new empirical flaw parameters were generated to match static and dynamic test results across several specimens. Figure 12— Figure 19 shows the cumulative Weibull distribution (failure probability) using both the original and adjusted set of flaw parameters plotted against the lateral pressure on the glass. Both models of the modified GFPM are shown for comparison.

The SBEDS-W model represents the model modified by PEC during the course of this project and uses an *m* value of 6.55 and *k* is treated as a constant (k=2.86e-53$N^{-7}m^{12}$). The RCSS version was run with both original flaw parameters (*m*=7, *k*=1.365 $lb^{-7}in^{12}$) and adjusted values (*m*=3, *k*=3.3e-15$lb^{-3}in^{4}$). To adjust the Weibull distribution parameters, several pairs of flaw parameters were plotted against the data until the cumulative distribution encompassed most test values (minimizing the number of test values in the tails of the distribution curve). This adjustment proved to be robust across multiple sizes, thicknesses, and load durations. Also, notice that the SBEDS-W model is consistently conservative and tuned for better correlation on dynamic test results (compared to the quasi-static tests).

Also, note that the resistance of the glass was not directly measured in dynamic testing (shock tube and blast testing) as material resistances are extremely difficult to measure directly when combined with inertial resistances. Resistance was thus inferred from measured deflection and known mass. The deflection was measured over time through the use of a laser gauge and the time of failure was determined from high-speed video. The resistance curve relates the deflection to the lateral pressure, and the time of failure was used to identify the maximum deflection and subsequent pressure (resistance) on the glass. So, the reported lateral pressure for dynamic testing should be treated with the appropriate level of confidence in this validation comparison.

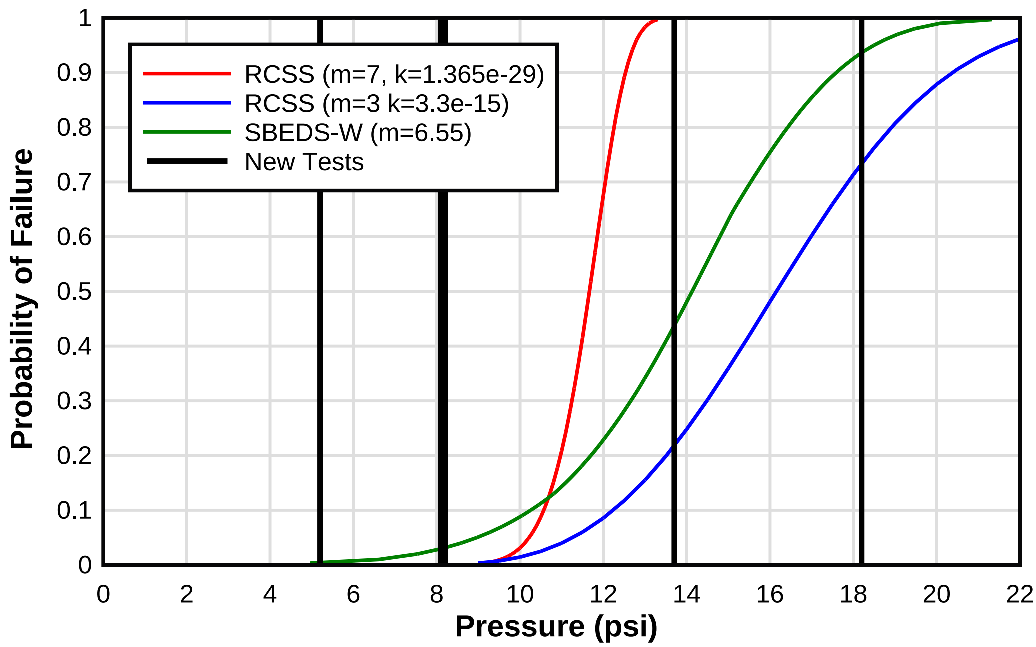


Figure 12. Dynamic Test Validation (60-in × 34-in × 0.220-in Monolithic Herculite® XP)

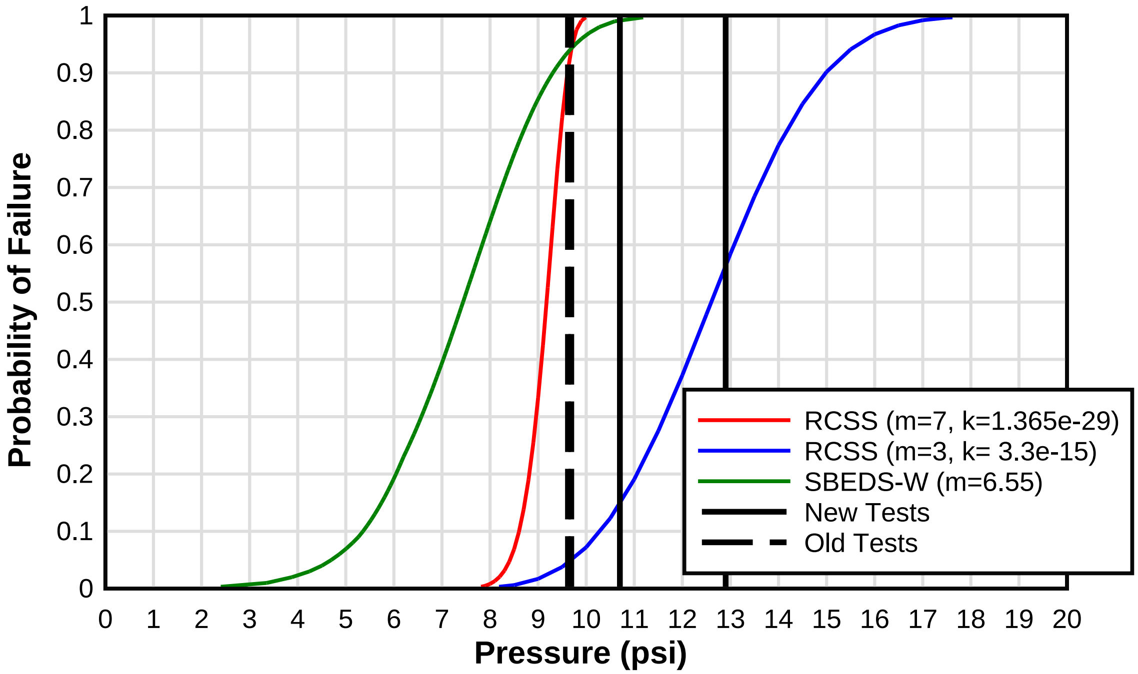


Figure 13. Static Test Validation (60-in × 34-in × 0.220-in Monolithic Herculite® XP)

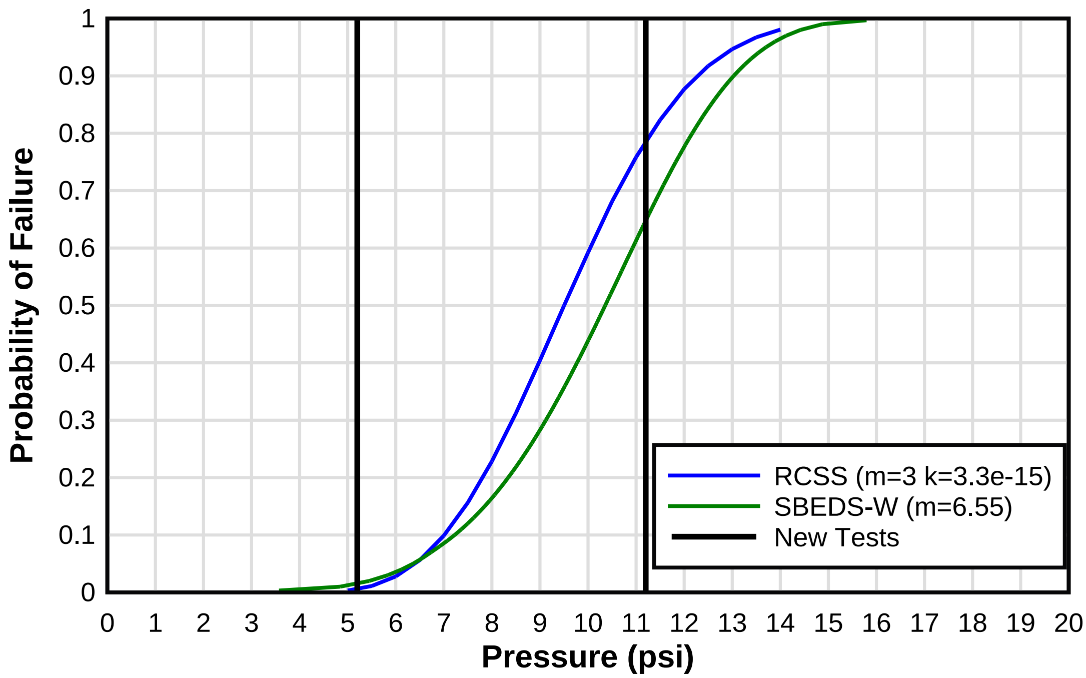


Figure 14. Dynamic Test Validation (60-in × 34-in × 0.180-in Monolithic Herculite® XP)

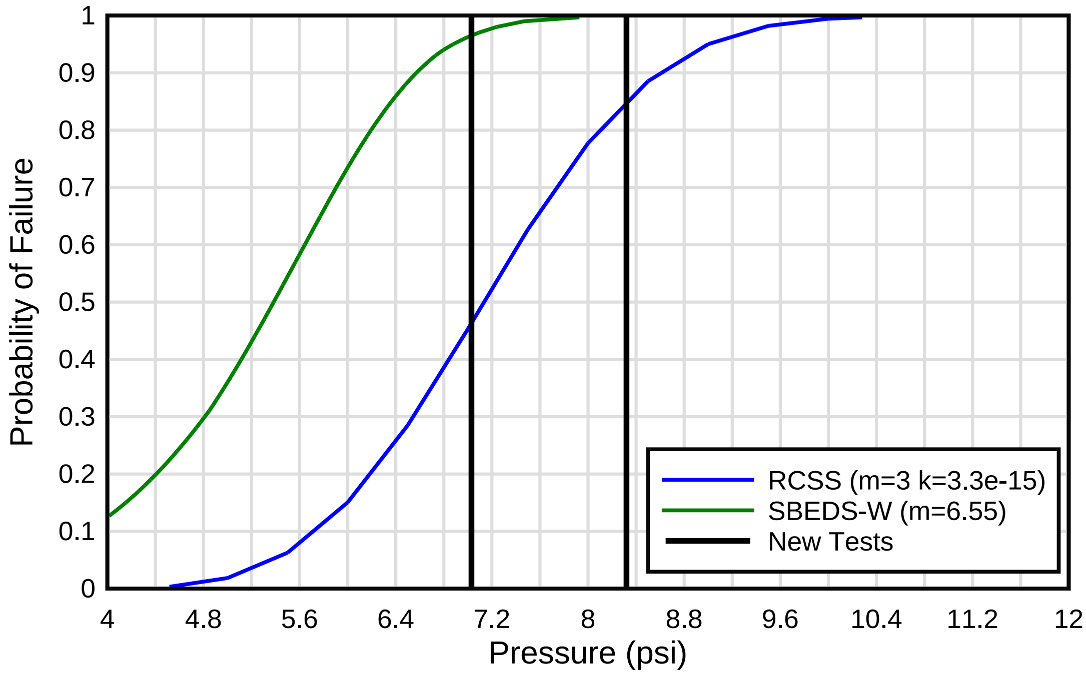


Figure 15. Static Test Validation (60-in × 34-in × 0.180-in Monolithic Herculite® XP)

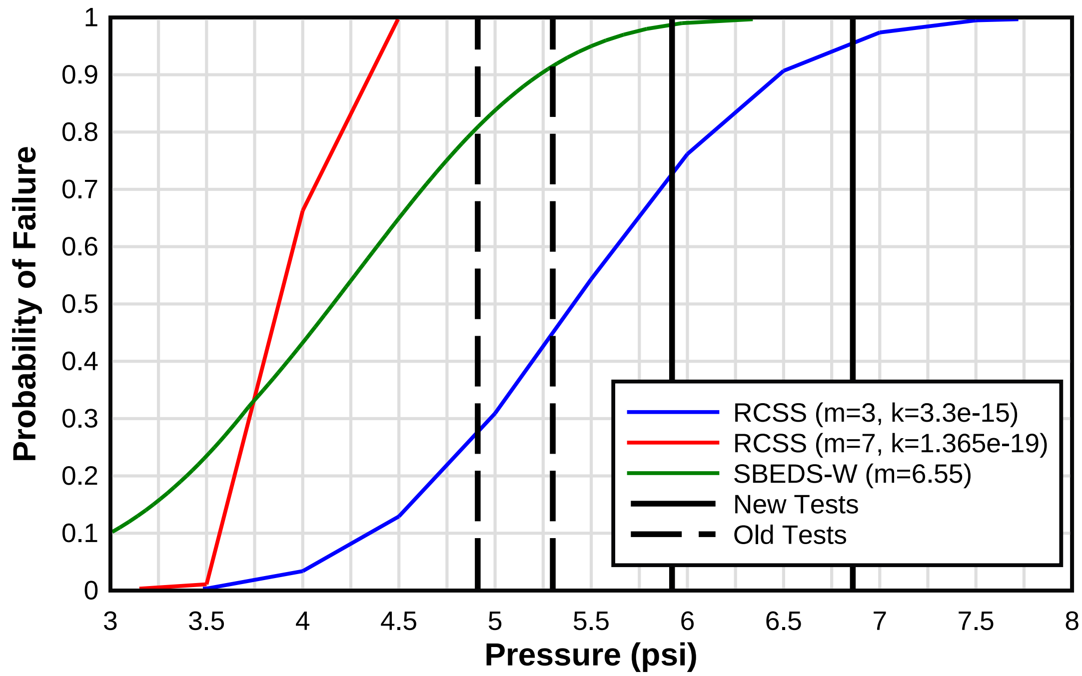


Figure 16. Static Test Validation (60-in × 34-in × 0.155-in Monolithic Herculite® XP)

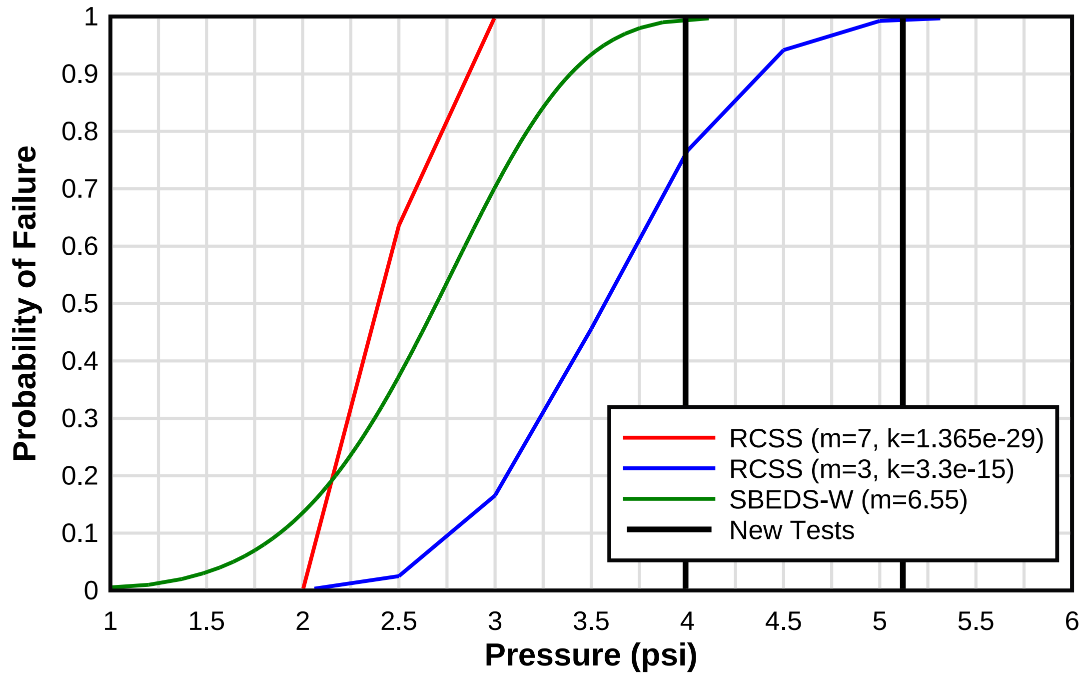


Figure 17. Static Test Validation (60-in × 34-in × 0.115-in Monolithic Herculite® XP)

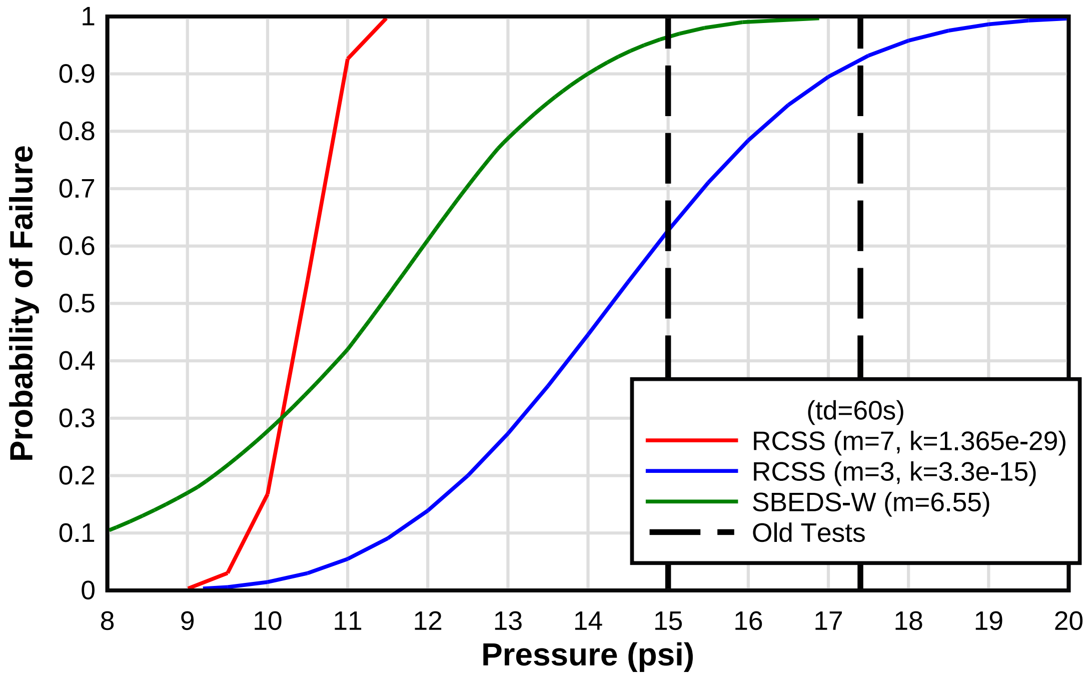


Figure 18. Static Test Validation (39-in × 27-in × 0.190-in Monolithic Herculite® XP)

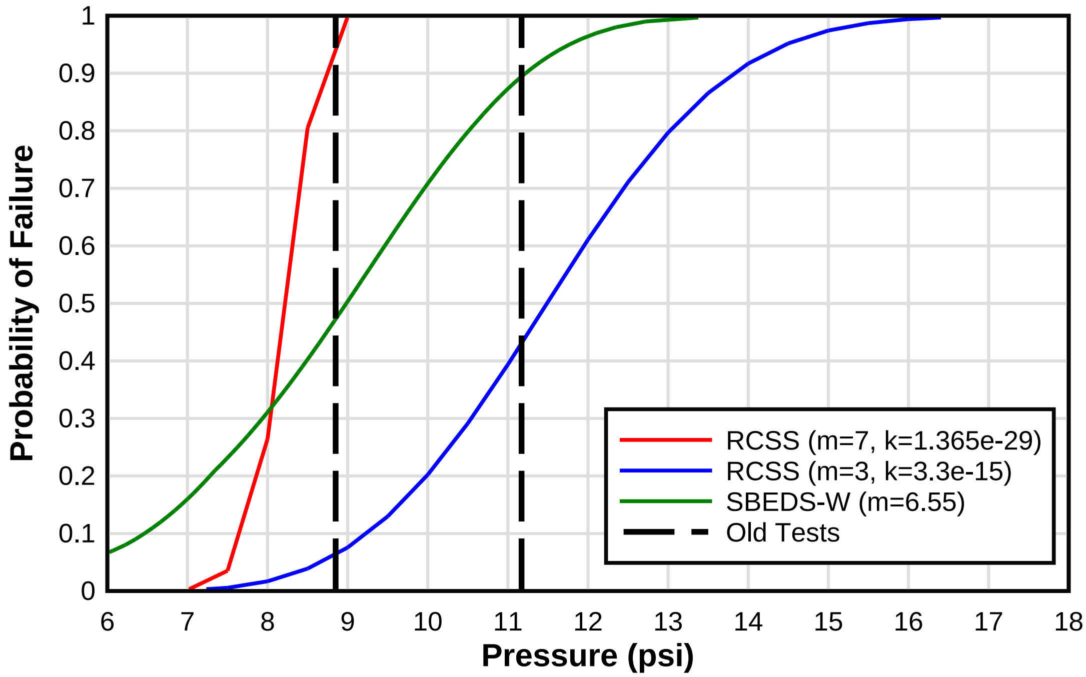


Figure 19. Static Test Validation (39-in × 27-in × 0.165-in Monolithic Herculite® XP)

The plots show conservative results from both models, with the RCSS GFPM model producing a more consistent distribution with a better envelope over the static test results, and the SBEDS-W implementation showing better results across the dynamic tests evaluated. SBEDS-W *m* factors were calibrated for dynamic results, thus biasing the factors for highly dynamic loads (the response regime of concern). The RCSS method was calibrated to match results regardless of load duration, thus allowing the load duration factor in the GFPM to account for changes in strength between the tests. This suggests that the SBEDS-W implementation is robust, and likely better accounts for uncertainties associated with high rate effects. The RCSS GFPM, however, is likely better for use with the ASTM static and static equivalent approaches.

5.3.3. Case Study (Design Example)

As shown above, two conservative and accurate models have been calibrated to predict the response of Herculite® XP; one better for blast/dynamic design and one better for use with the static or static equivalent design approaches of ASTM E1300 (with ASTM F2248 equivalent static loading). Examples of both methods are included as follows.

5.3.3.1. Dynamic Design Methodology

Dynamic design can incorporate several different computation methods, such as SDOF or FEA to calculate the glass response. For this report, SDOF will be used as the computational methodology.

Without going into too much detail on SDOF theory, an SDOF utilizes a resistance curve to correlate the force/deflection relationship of the geometry and material of the structural element. In this case, it is a rectangular piece of glass simply supported along all sides with varying length, width, and thickness dimensions. The resistance curve can be calculated using SBEDS-

W, which incorporates the GFPM procedures found in Appendix X2 of ASTM E1300. Appendix X2 provides a polynomial equation that correlates the lateral pressure on the glass to the deflection at midspan. An example resistance function from SBEDS-W is shown in Figure 20.

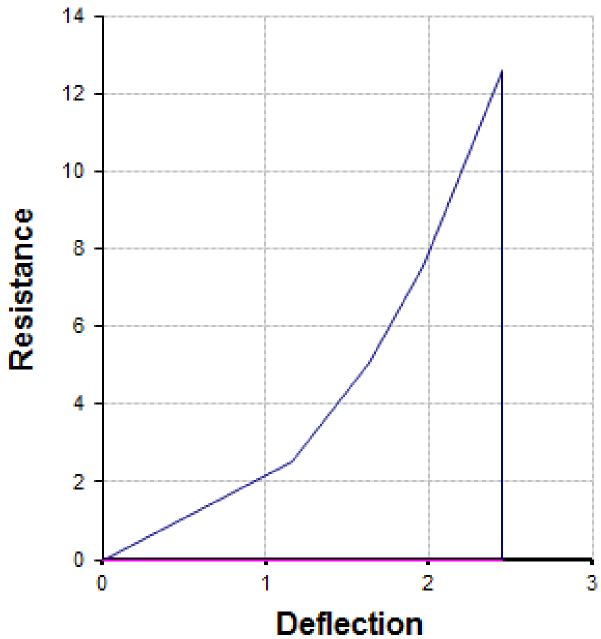


Figure 20. Resistance vs. Deflection Curve Provided by SBEDS-W

The soon-to-be-released version of SBEDS-W does not currently have the modifications needed to run Herculite® XP, but it can be added in future releases. Nevertheless, an example is included to show the analysis procedure using this tool. It has been updated internally to allow for SDOF analysis/predictions using Herculite® XP over the course of this project. SBEDS-W uses the GFPM to evaluate glass failure criteria and varies the flaw parameter *m* to account for glass strength (m = 6.55 for Herculite® XP) and treats the *k* parameter as constant.

This example utilizes a 60-in × 34-in × ¼-in Herculite® XP glass lite and the corresponding resistance curve is shown in Figure 20. Figure 21 shows a screenshot of SBEDS-W configured for this glass pane, as well as an example charge weight and standoff.

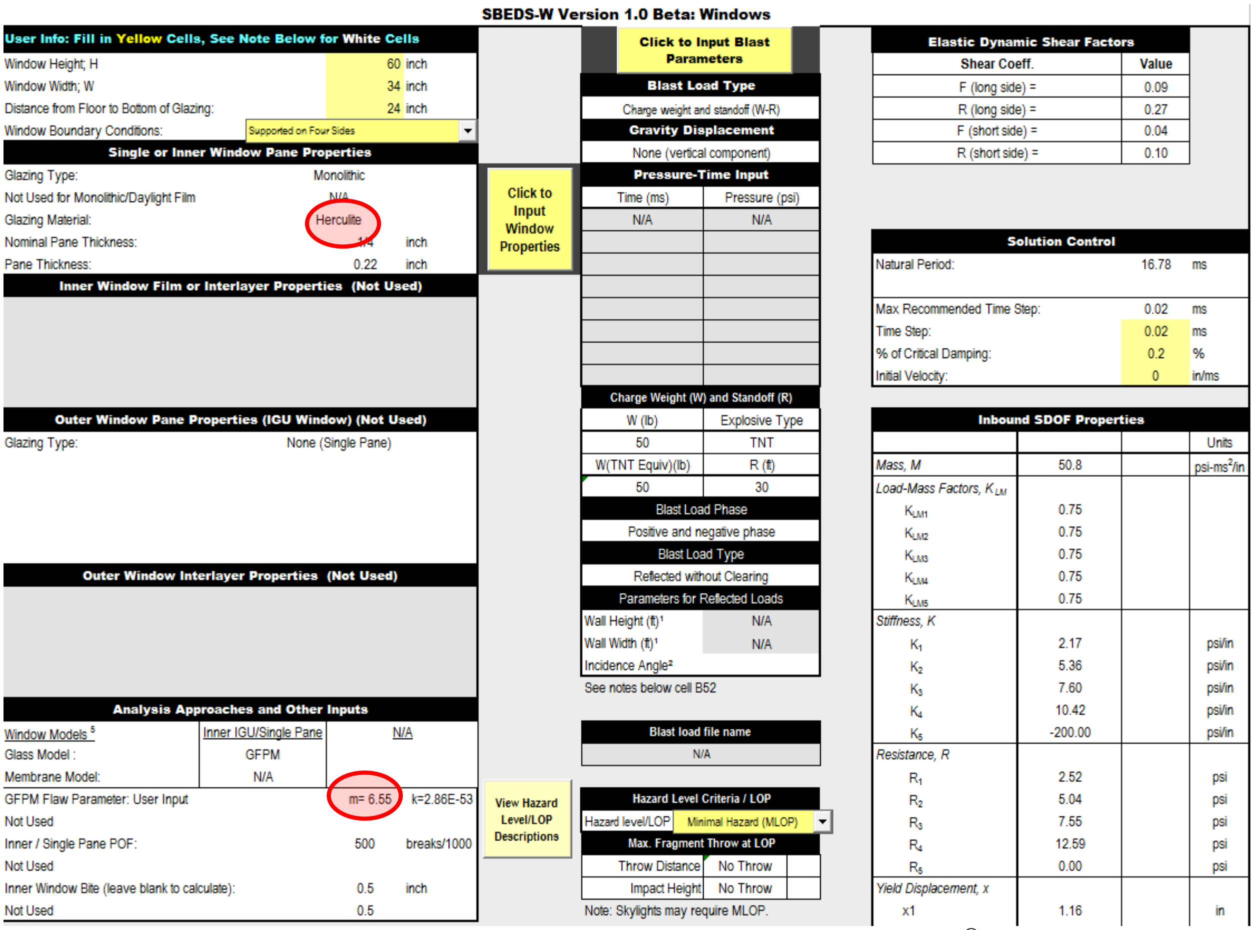


Figure 21. SBEDS-W with Modifications for Herculite® XP

With this tool, analyzing Herculite® XP for blast loads is as simple as specifying glass dimensions and the blast load. Figure 22 and Figure 23 show the results for a 70-ft and 60-ft standoff, respectively. At 70-ft, the blast load did not cause enough response in the glass to initiate failure, as shown by the displacement history where free oscillation is evident. However, if the charge is moved 10-ft closer to a 60-ft standoff, the blast load creates enough response in the glass to initiate fracture, as shown by the abrupt end to the displacement curve at 6.3ms.

This method of analysis is robust and provides quick, simple, and conservative results as a design tool for Herculite® XP. However, this tool is not currently available in industry and modifications to SBEDS-W would need to be incorporated into a future release.

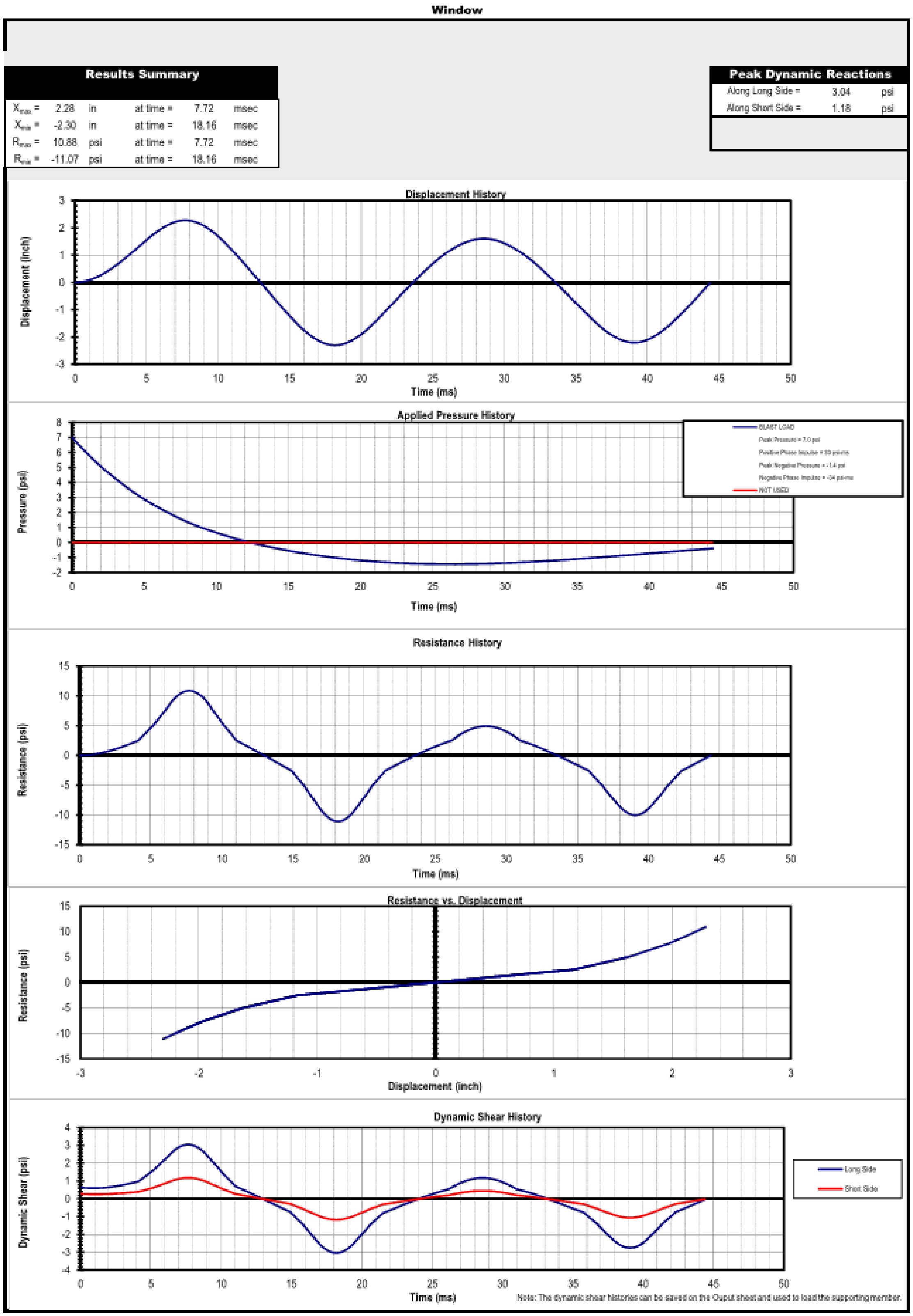


Figure 22. SBEDS-W Output with 70-ft Standoff

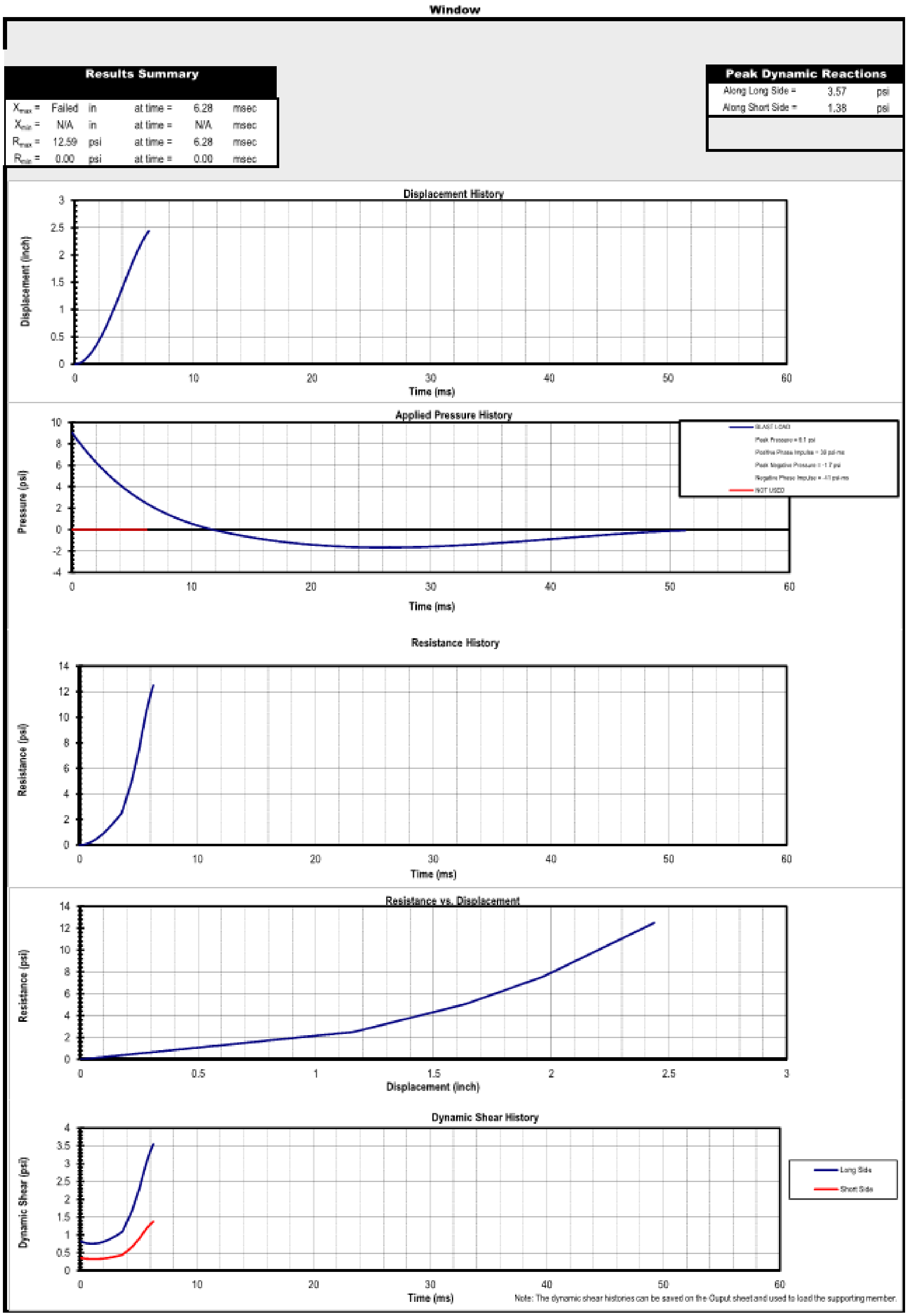


Figure 23. SBEDS-W Output with 60-ft Standoff

5.3.3.2. Static Design Methodology

ASTM E1300 coupled with ASTM F2248 provides engineers with a conservative methodology for sizing glass for blast loads with a static design approach. ASTM F2248 provides a chart (Figure 24) linking blast loads to an equivalent 3 second wind load for use with ASTM E1300 design procedures. When applied to Herculite® XP, however, the chart appears to be inadequate; the blast loads that the glass can withstand are either off the chart or are not conservative enough for Herculite® XP. For example, the load for Blast Test 1 is shown with red crosshairs on Figure 24. This indicates that the blast load of 250 lbs at 70-ft is equivalent to a design wind load of 8.5 kPa (175 psf). The wind load capacities shown in Figure 25 indicate the Herculite® XP can withstand nearly 50kPA (1045 psf). However, based on the dynamic analysis previously presented, this blast load results in glass failure while this static method indicates the glass would perform well. Therefore, a new chart linking blast load to equivalent wind loads for Herculite® XP need to be developed.

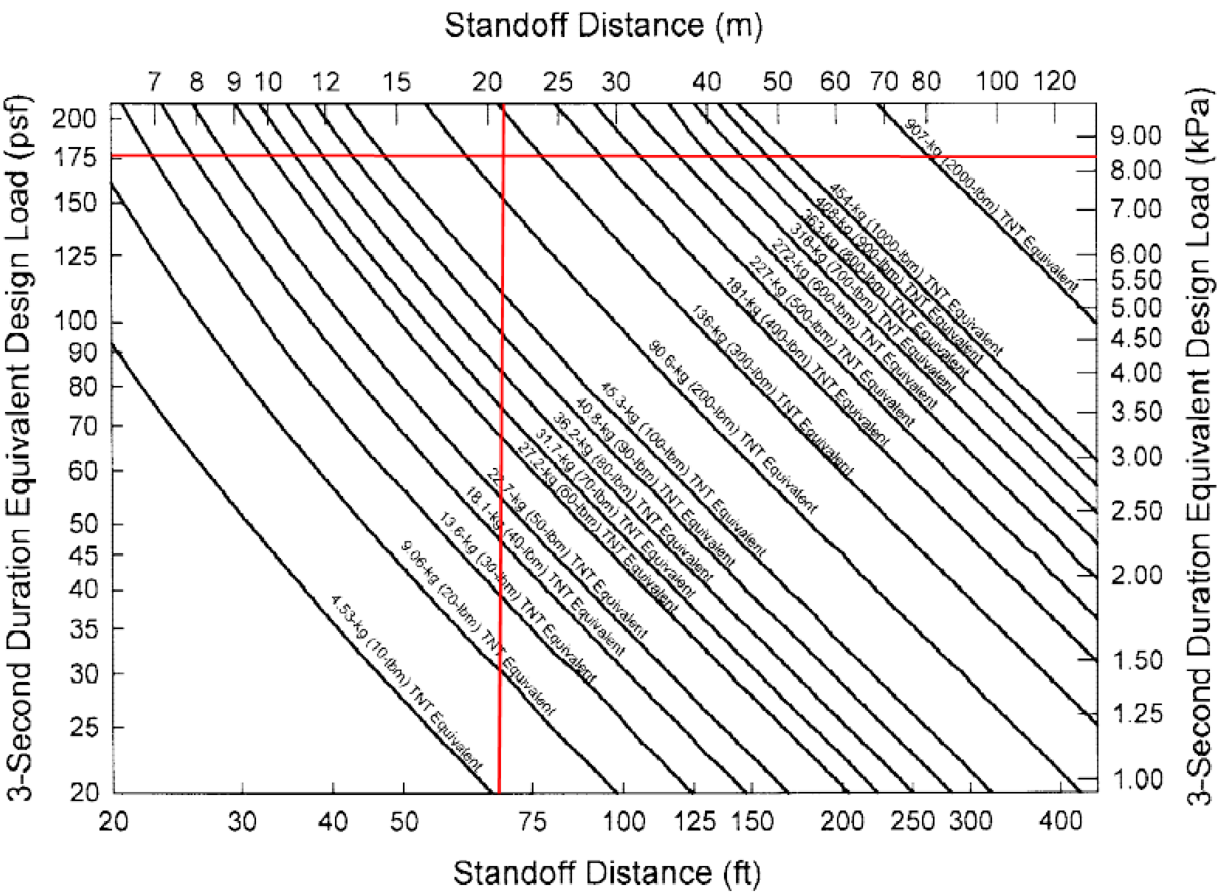


Figure 24. ASTM F2248 Chart relating Charge Weight and Standoff to a 3-Second Duration Equivalent Design Load

Figure 25 shows an example wind load chart for Herculite® XP that incorporates the RCSS GFPM described above. Compare the difference in loads between the AN glass in Figure 26 and the Herculite® XP in Figure 25. For a 60-in × 40-in × ¼-in pane of glass, the AN glass is rated at around 2.75kPa and Herculite® XP is rated for nearly 50kPa.

Though the current chart in ASTM F2248 is not adequate for use with Herculite® XP, a similar chart could be developed using dynamic analysis and test data. However, static design is inherently conservative and dynamic analysis will yield better use of Herculite® XP.

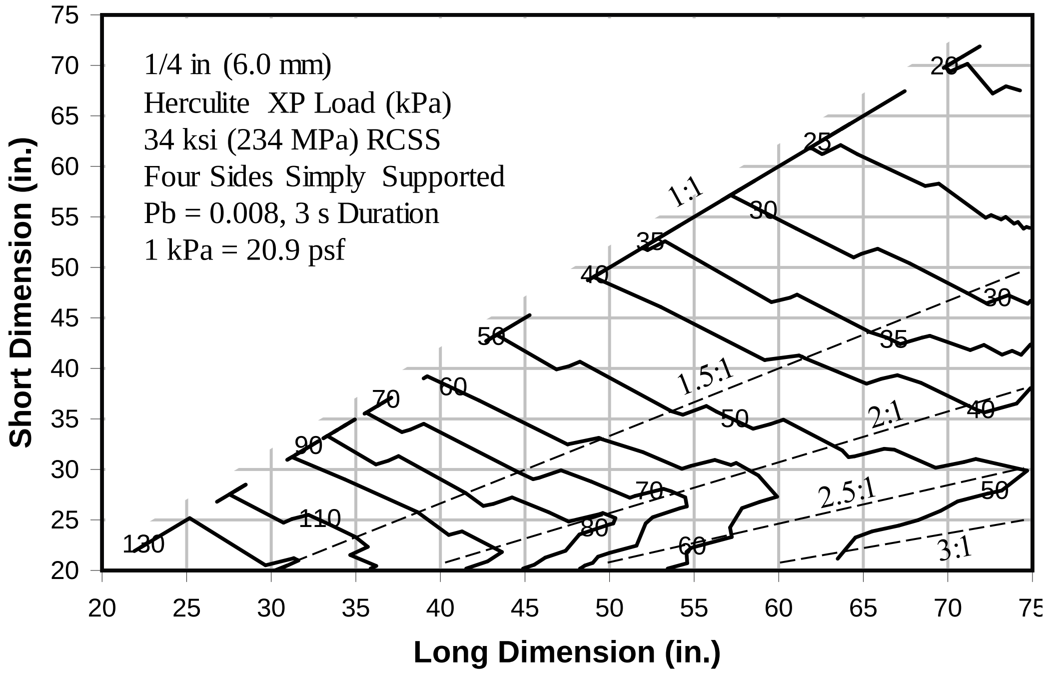


Figure 25. Herculite® XP Wind Load Deflection Chart

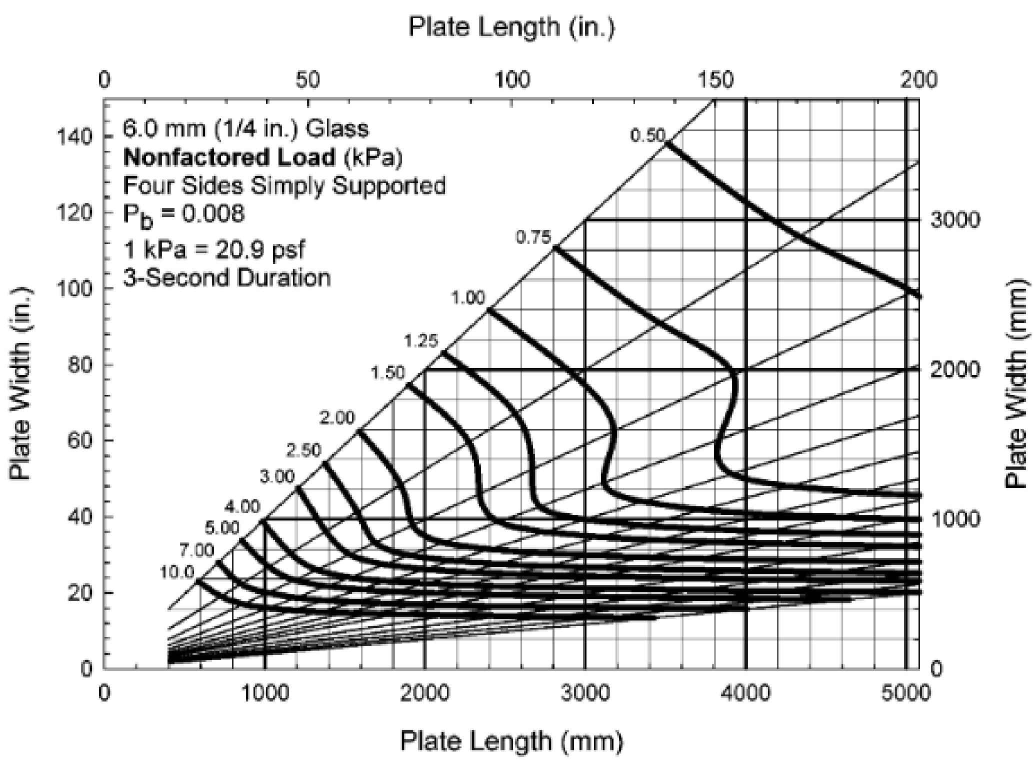


Figure 26. Nonfactored Load Chart from ASTM E1300

In conclusion, Herculite® XP has much higher strength than current AN, HS and FT glass and the current design procedures will need to be modified to accommodate this increase in strength. Industry standard design procedures found in ASTM E1300 are built on the GFPM which have been incorporated into dynamic analysis methods in SBEDS-W and can be expanded to include Herculite® XP. Likewise, GFPM can be incorporated into static and static equivalent design methodologies through the use of design charts similar to those found in ASTM E1300 and modified for Herculite® XP.

For static analysis, the chart used to equate blast load to wind load in ASTM F2248 is inadequate for Herculite® XP. A customized version for Herculite® XP could be developed in the future to provide designers with a static design option. However, to get the full benefit out of the additional strength in Herculite® XP, a dynamic analysis is more accurate and better utilizes the material strength. With a high-strength model validated, future work can be done to further develop design charts specifying the resistance and deflection threshold for any given piece of glass. Overall, the modification to the GFPM provides industry with the capability to predict and design with high-strength glass such as Herculite® XP.

6. CONCLUSIONS

PPG's consultant PEC has completed a review of the static and dynamic test data, flexural models, and injury predictions for Herculite® XP glazing and has drawn several important conclusions, as summarized below.

Herculite® XP glass was evaluated statically and dynamically to confirm and update design parameters from a previous research program with PPG Industries on the development of Herculite® XP. The design parameters were used in a robust resistance function for dynamic SDOF analysis of Herculite® XP. The SDOF analysis tool conservatively predicted the performance of Herculite® XP IGUs in standard layups subjected to shock tube and blast loads. In general, Herculite® XP can provide the same level of protection as AN, HS, or FT glass using a thinner section.

Herculite® XP glass was tested dynamically in punched-window and storefront configurations using standard commercial mullion framing systems. Tests illustrated that commercial mullion systems can successfully support Herculite® XP glass when subjected to blast loads. Blast tests also illustrated that for blast loads with high pressures, the glass and mullion response was essentially uncoupled and can be conservatively designed using SDOF analysis.
However, a coupled analysis may be more appropriate for more complex curtain wall systems with varying support conditions. Thus, data collected will help validate future MDOF design tools of glass and mullion systems.

A design method has been developed and illustrated to enable engineers to specify Herculite® XP for windows in various facilities using a consensus standard. Herculite® XP glass can be incorporated into ASTM E1300 using a proposed approach outlined by the ASTM task group with minor modifications. Data collected during the test program was used to adjust the approach specifically for Herculite® XP applications. A full example including all design assumptions is provided.

7. RECOMMENDATIONS

Recommendations for future work based on the results of this research and development program include:

Using the blast test data to better refine existing parameters used in SDOF design approaches. The DIC data will be extremely valuable in future updates to these tools, particularly with respect to deformed shape and strain rate and strain distribution assumptions used for PVB membrane response. Current PVB failure limits and strains are based almost exclusively on observed deformation limits. Observed strain distributions could be used with material rate models to quantitatively define failure criteria. The DIC data and mullion response data would also be well used to further develop a MDOF model for glass and mullion system response. Coupled FEA and engineering models currently exist (WinGARD-MP) (GSA, 2006), which rely on the same glass and PVB deformed shape assumptions used for punched windows.

Working with glass experts at PPG and other glass manufacturers to optimize other "super-tempered" glass which could be used in architectural blast or impact resistant applications. Quantifying the performance of varying degrees of "super-tempering" would better facilitate manufacture and selection of glass (and have expenditure benefits) for varying load environments.

8. REFERENCES

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

°F	degrees Fahrenheit
ABS	ABS Consulting
AN	annealed
ASTM	American Society for Testing and Materials
ATFP	antiterrorism/force protection
aver.	average
defl.	deflection
deg	degree
DIC	digital image correlation
dim.	dimension
DLO	daylight opening
fab.	fabrication
FEA	finite element analysis
FT	fully tempered
ft	foot; feet
ft/s	feet per second
g	gram
GFPM	Glass Failure Prediction Model
HS	heat strengthened
IGU	insulating glass unit
in	inches
in^2	square inches
kPa	kilopascals
lbs	pounds
m	meter
LLOP	low level of protection
max.	maximum
MDOF	multi-degree of freedom
MHGP	multi-hit glass penetration
mm	millimeter
MPa	megapascal
ms	millisecond
N	Newton
N/A	not applicable
N/M	not measured
no.	Number
PEC	Protection Engineering Consultants
psf	pounds per square foot
psi	pounds per square inch
PSLLC	Physical Security, LLC
PVB	poly-vinyl butyral
RCSS	residual compressive surface stress
s	second
SBEDS-W	single degree of freedom blast effects design spreadsheet for windows
SDOF	single degree of freedom

temp.	temperature
TNT	trinitrotoluene

GLOSSARY OF TERMINOLOGY

ANNEALED GLASS (AN)—The most common glass type used in construction. It is also the weakest glass type and fails in large hazardous dagger-like fragments

FRAME—The outer members of a window. The frame includes the head, sill or threshold, the two jambs and the meeting rail of a window.

FULLY TEMPERED GLASS (FT)—This glass type is about four times the compressive strength of regular annealed glass. FT is the same glass used by car manufactures for side windows in automobiles. It is often called safety glass. FT glass tends to dice into small cube like pieces upon failure.

GLASS—Any of a large class of materials with highly variable mechanical and optical properties that solidify from the molten state without crystallization. They are typically based on silicon dioxide (sand), boric oxide, aluminum oxide, or phosphorus pentoxide, generally transparent or translucent, and are regarded physically as supercooled liquids rather than true solids.

GLAZING—The transparent material held within the window frame. Various types of glass and/or plastic are the most common glazing materials.

HEAT STRENGTHENED GLASS (HS)—This glass is produced in much the same way as tempered glass, but with lower levels of surface compression, 3500–7500 psi. The final product is two times stronger than annealed glass. The break pattern varies with level of surface compression with lower levels having a break pattern similar to annealed glass and higher levels resulting in patterns similar to tempered glass.

INSULATED GLASS—A light of glass made up of two sheets of glass, a spacer bar filled with a desiccant material placed between the two sheets at the perimeter, and a sealant applied around the entire perimeter of the assembly. This assembly creates an envelope of dead air which when used in a window or door, greatly reduces the passage of heat through the glass, thereby producing a savings at an increased material cost.

INSULATING GLASS UNIT (IGU)—consists of two separate panes of glazing separated by a hermetically sealed airspace of constant thickness. See insulated glass.

LAMINATED GLASS—Two or more plies of glass bonded together by interlayer(s). When fractured, the interlayer tends to retain the glass fragments.

LITE—A piece of glass in a window. Another term for a pane of glass used in a window. Frequently spelled "lite" in the industry literature to avoid confusion with light as in "visible light".

PANE— A lite of glass.

Definitions from UFC 4-023-04 Blast, Ballistic, and Forced Entry Resistant Windows (2007)